Cost Benefit Analysis of Reusing Electric Vehicles Batteries: A Circular Economy Perspective

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THESIS ACCEPTANCE CERTIFICATE

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Dedication

Dedicated to my exceptional parents, adored siblings, and loving grandparents whose tremendous support, cooperation and prayers led me to this wonderful achievement.

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First and foremost, I express my gratitude to Allah, the Almighty, for His abundant blessings and strength, without which I would not have been able to successfully complete my research.

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LIST OF ABBREVIATIONS

EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
BEV	Battery Electric Vehicle
FCV	Fuel Cell Vehicle
ICE	Internal Combustion Engine
kWh	Kilowatt-hour
kW	Kilowatt
kWh/100 km	Kilowatt-hour per 100 kilometers
SOC	State of Charge
BMS	Battery Management System
CFD	Computational Fluid Dynamics
LCA	Life Cycle Assessment
V2G	Vehicle-to-Grid
OBC	On-Board Charger
DCFC	Direct Current Fast Charging
AC	Alternating Current
DC	Direct Current
SLB	Second Life Batteries
CBA	Cost Benefit Analysis

CE	Circular Economy
PV	Photo Voltic
IRR	Internal Rate of Return
NPV	Net Present Value

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ABSTRACT

The feasibility of reusing electric vehicle (EV) batteries from a circular economy (CE) perspective is examined in this research study. As the adoption of EVs continues to grow, the question of what happens to their batteries once they reach the end of their useful life becomes increasingly important. This study explores the potential for reusing EV batteries, considering economic, environmental, and social factors. The research investigates the economic viability of reusing EV batteries by analyzing the costs and benefits associated with the reuse process. It considers factors such as the initial investment required for refurbishment, the market demand for used batteries, and the potential revenue streams from their reuse in various applications. Additionally, a sensitivity analysis is performed to identify critical variables that can affect the economic feasibility of battery reuse. From an environmental perspective, the study examines the impact of reusing EV batteries on resource conservation, energy consumption, and carbon emissions. It evaluates the potential reduction in greenhouse gas emissions and the conservation of valuable materials that can be achieved through battery reuse. The study also addresses the challenges and opportunities of managing end-of-life (EOL) batteries within a CE framework. Furthermore, the social implications of reusing EV batteries are analyzed, considering factors such as job creation, community engagement, and public perception. The study investigates the social acceptance of reused batteries and potential concerns related to safety and reliability. It explores the role of policymakers in facilitating the transition to a CE for EV batteries and identifies strategies to address societal barriers. This research provides insights into the feasibility of reusing EV batteries from a CE perspective. It highlights the potential economic, environmental, and social benefits of battery reuse and identifies key challenges that need to be addressed. The findings of this study can inform decision-makers, industry stakeholders, and policymakers in developing strategies to maximize the value and sustainability of EV batteries throughout their lifecycle.

Keywords: CBA, electric vehicle batteries, circular economy, feasibility, economic viability, environmental impact, social implications, second life.

CHAPTER 1. INTRODUCTION

This chapter contains introduction of electric vehicles (EV) batteries, the study's rationale, its defined problem, and its stated goals.

Pakistan is ranked as the fifth most populous country globally, leading to a substantial number of vehicles in the nation. The country currently has nearly 24 million two and three-wheelers, four million passenger cars, and around half a million buses and trucks. Although Pakistan has a relatively low number of EVs, with approximately 2,000 all-electric passenger cars and a few fast-charging stations, the demand for EVs is rising due to the escalating petroleum prices. To encourage the adoption of electric transportation, the Government of Pakistan (GoP) has introduced incentives and policies, creating a new untapped market for the EV industry.

The GoP has set targets to increase the sales of EVs by 30-50% of the total annual vehicle sales, aiming to reduce the reliance on internal combustion engine vehicles (ICEV), which contribute to air pollution and high gasoline import bills. To promote EV adoption and domestic manufacturing, the GoP has implemented various incentives and tax breaks:

1. EV-specific parts, including batteries, motors, and motor control units, can be imported with only a 1% customs duty (CD), compared to the 25% CD imposed on non-EV specific parts.
2. Indigenously manufactured EVs are subject to a reduced general sales tax (GST) of 1%, instead of the standard 17% GST.
3. Duty-free import of machinery and hardware is permitted to establish EV and EV-specific parts manufacturing facilities.
4. Corporate income tax has been waived for companies engaged in the manufacturing of EVs and EV-specific parts.
5. Provincial governments have been instructed to lower registration rates and yearly token taxes for EVs.

Furthermore, the GoP provides additional facilities such as expedited electricity connections for charging stations and reduced electricity rates. International development cooperation agencies such as USAID, World Bank, Asian Development Bank, United Nations Development Program, and others support the GoP's efforts in various technical areas, including EV penetration scenarios, charging infrastructure development, financing, and standardization.

Regarding electricity supply and demand, Pakistan currently possesses sufficient electricity generation capacity to fulfill the charging requirements of EVs in the short to medium-term. Despite having a total electricity generation capacity of 202 TWh in 2019, only 128 TWh was utilized. By 2025, the country is expected to have 293 TWh of electricity generation capacity, with an estimated utilization of 202 TWh. This leaves ample generation capacity for transitioning the transportation sector to EVs without compromising the energy demands of other sectors.

In terms of batteries, they play a crucial role in EVs. To meet the GoP's EV penetration targets, Pakistan would require a battery storage capacity of 60-80 GWh. Additionally, the country has a significant market for stationary battery storage, driven by the installation of uninterruptible power supply (UPS) systems for reliable electricity provisioning. Currently, Pakistan has approximately 2.8 million UPSs with a battery storage capacity of around 6 GWh. Another notable demand for battery storage in the country arises from the telecommunication sector, which projects a 17% annual increase in the number of telecommunication towers.

By 2025, Pakistan is projected to have over 100,000 telecommunication towers, necessitating more than 3.5 GWh of battery storage capacity. The GoP has also set a target to increase the contribution of renewable energy (solar and wind) to 30% of the national energy mix by 2030. This renewable energy expansion, estimated at approximately 7,300MWp, will create additional demand for batteries to address the intermittent nature of renewable power generation. Another sector requiring battery storage is the reefer truck industry, which currently operates 3,000 refrigerated containers in Pakistan, necessitating 144MWh of battery capacity. Considering the requirements of multiple sectors, Pakistan is anticipated to need approximately 100GWh of battery storage capacity in the next decade. While lead-acid batteries are presently used, the country seeks new battery technologies to meet emerging demands. The proliferation of EV is crucial to the development of environmentally friendly transportation. The transportation industry is a major source of pollution, and the European Union (EU) has set a goal of reducing transportation-based carbon emissions to 37.5% by 2030. (European Commission, 2021)

1.1 Potential Use of EVs

EVs have become increasingly essential in our pursuit of sustainable transportation. Firstly, EVs significantly reduce greenhouse gas emissions compared to conventional ICEVs. As the transportation sector is a major contributor to global carbon dioxide emissions, transitioning to EVs plays a crucial role in mitigating climate change. According to a study conducted by the Union of Concerned Scientists, even when accounting for emissions from electricity generation, EVs produce lower emissions over their lifetime compared to gasoline-powered vehicles. Additionally, the increasing availability of renewable energy sources for electricity generation further enhances the environmental benefits of EVs.

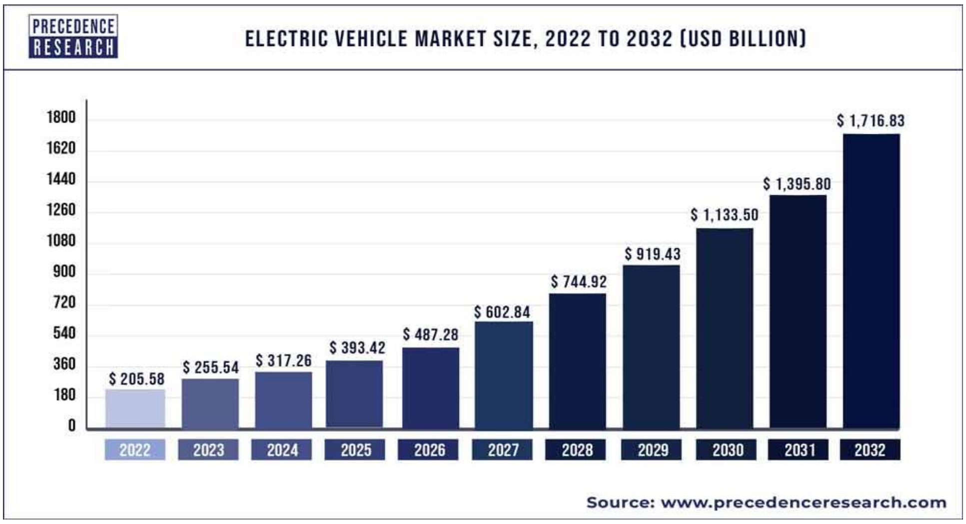

Figure 1: Market Size of EV

Firstly Figure 1[1] shows the market share of EV batteries which stands at 391$ while it is predicted that in 2032 it will be at 1716$. The predicted increase from $391 billion to $1,716 billion implies a significant growth rate for EV batteries over the specified time period. This growth can be attributed to several factors, including the increasing demand for EVs, advancements in battery technology, government incentives, and efforts to reduce carbon emissions. Secondly, EVs contribute to improved air quality, reducing pollution in urban areas. ICEVs emit harmful pollutants such as nitrogen oxides (NOx), particulate matter (PM), and volatile organic compounds (VOCs), which have adverse effects on human health. In contrast, EVs produce zero tailpipe emissions, thereby minimizing local air pollution. A study published in the journal Science Direct indicates that widespread adoption of EVs could lead to a

[1] https://www.precedenceresearch.com/electric-vehicle-market

significant reduction in air pollution and related health issues, particularly in densely populated cities. This improvement in air quality positively impacts public health, reducing respiratory problems and cardiovascular diseases.

Overall, the adoption of EVs is essential for addressing climate change, reducing greenhouse gas emissions, and improving air quality. Their environmental benefits, coupled with the increasing availability of renewable energy sources, make EVs a promising solution for sustainable transportation.

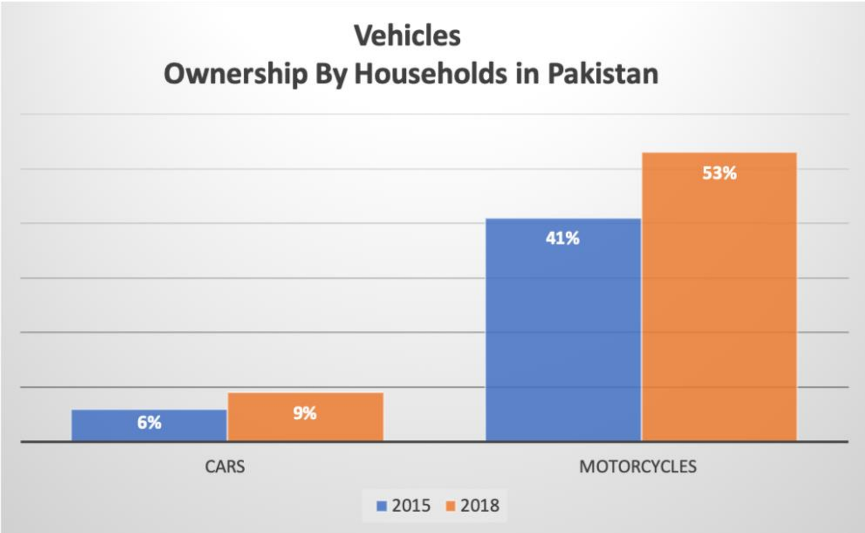

Figure 2: Ownership in Pakistan (Haq, 2019)

Figure 2 describes that the ownership of motorcycles increased from 41% to % 53% while cars ownership increased from 6% to 9%. (Haq, 2019) however, over the past decade, EV sales in Pakistan have witnessed a steady increase. This growth can be attributed to several factors, including government incentives such as low tax breaks offered to buyers of EVs and the imposition of taxes on gas-guzzlers. These measures have encouraged the adoption of EVs and contributed to the shifting automotive landscape in the country (Government of Pakistan, 2021). As EV adoption continues to rise, there are implications for energy consumption and the distribution infrastructure. The increased usage of EVs may lead to new peaks in energy demand patterns, requiring adjustments in the electricity grid's capacity and distribution systems (Khan, 2020). However, EVs also offer the potential to serve as a future storage solution through their Vehicle-to-Grid (V2G) capabilities. V2G technology enables EVs to not only draw power from the grid but also return excess electricity back to the grid during peak demand periods, effectively functioning as mobile energy storage units (Farooq et al., 2022).

1.2 Reuse of Batteries

Batteries, especially those used in EVs and renewable energy storage systems, hold significant potential for reuse. The rapid growth of EV adoption and the increasing demand for energy storage solutions have led to a substantial increase in the number of used batteries becoming available. Rather than being disposed of, these batteries can be repurposed for various applications, extending their lifespan and maximizing resource utilization (Parfomak, 2021). Reusing batteries can help alleviate the environmental impact associated with their production and disposal, as well as reduce the demand for new raw materials.

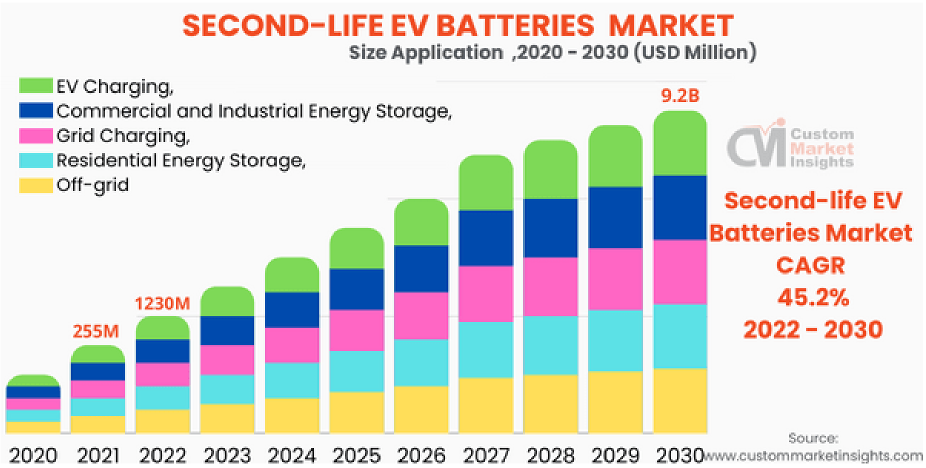

Figure 3: Super Life EV batteries market (Joel, 2023)

Furthermore Figure 3[2] gives an insight of second life EV batteries market stands at 1230M$ while in 2030 will be 9.2B$ (Joel, 2023). This further shows that the second life of EVs batteries market will be high in future. One promising avenue for battery reuse is in stationary energy storage systems. Even after reaching the end of their useful life in EVs, batteries typically retain a significant portion of their capacity, making them suitable for less demanding applications such as grid-scale energy storage. By connecting used batteries to energy grids, they can store excess renewable energy generated during periods of low demand and supply it back to the grid during peak hours (Liu et al., 2020). This not only helps balance supply and demand but also enhances the integration of renewable energy sources, promoting a more sustainable and resilient energy system.

[2] https://www.custommarketinsights.com/report/second-life-ev-batteries-market/

As the popularity of EVs continues to grow, there will be an increasing demand for the recycling of spent batteries. Typically, EV batteries are considered no longer suitable for vehicle use once their capacity drops to around 20% of their initial value (Heymans et al., 2014). However, these discarded lithium-ion EV batteries still retain enough usable life to serve other purposes, such as stationary storage, known as Second Life Batteries (SLB). It is estimated that by 2025, there will be approximately 3.4 million discarded EV batteries, collectively offering a capacity of 953 GWh (Dessaint, 2019, as cited in Fig. 3). Utilizing these batteries in fixed locations can be particularly beneficial when storage space is limited, reducing the need for additional raw materials for manufacturing new Lithium-ion batteries (LIB). This not only minimizes environmental harm but also contributes to the principles of a CE.

Nevertheless, battery storage devices have proven to be valuable as short-term storage technologies, aiding the grid in meeting future demands. Like well-managed dynamic storage systems, fleets of EVs can also generate economic and environmental benefits, creating new revenue streams through vehicle-to-grid (V2G) and vehicle-to-building (V2B) systems, alongside residential applications like vehicle-to-home (V2H). Despite the advantages, second-life batteries (SLBs) face challenges related to their battery components, hindering their widespread adoption.

Figure 4: Lithium-Ion Battery recycling worldwide

The figure 4[3] shows that recycling of Lithium ion batteries worldwide. This data from 2020 to 2030 shows that the recycling market of these batteries will reach at 38.2 billion dollars from

[3] https://www.researchandmarkets.com/reports/4804027/lithium-ion-battery-market-report-by-type

1.76 B$. The global market for recycling LIBs is divided into several segments, including battery chemistry, source, recycling process, end use, and region. In terms of battery chemistry, the market is categorized into different types, such as lithium-iron phosphate, lithium-manganese oxide, lithium-nickel-cobalt-aluminum oxide, lithium-nickel-manganese-cobalt, and lithium-titanate oxide (Researchandmarkets, 2022). The source of these batteries determines their origin and is classified into EVs, electronics, power tools, and others. The recycling process used in the market can be further broken down into the hydrometallurgical process, physical/mechanical process, and pyro metallurgy process. Depending on the purpose of recycling, the market is divided into automotive and non-automotive sectors. Finally, the market is analyzed based on different regions across the globe. This expanded network has the potential to significantly impact the circular economy (CE), emphasizing the importance of extending SLB applications beyond EV owners. EV owners play a pivotal role in sustainable energy consumption, transforming from passive to active consumers. With a lifespan of up to 30 years, second-life batteries contribute to the principles of the CE, aligning with the European Union's Circular Economy Action Plan that aims to minimize material waste and promote reuse and recycling practices, with particular focus on batteries and transportation systems (Casals et al., 2019; European Commission, 2021).Discarded batteries may experience a decline in capacity or power due to various factors, such as structural changes like cathode and anode degradation, high cycling rates, overcharging, and discharging. To determine their suitability for reuse, EV batteries that have been deemed unfit undergo a thorough screening, sorting, testing, and processing procedure. These batteries, depending on their remaining capacity, can serve multiple purposes.

1.3 Applications of Second Life Batteries

One potential application for SLBs is their use by homeowners and commercial property owners to store energy generated from renewable sources like solar and wind. This versatile setup can be implemented on both small and large scales, with or without grid access. It offers benefits such as peak shaving, where consumption peaks are artificially reduced in industrial settings, and enabling homeowners to charge their EVs when electricity rates are low. By storing energy, SLBs enhance the adaptability, efficiency, and reliability of the grid, facilitating the integration of more renewable sources. Furthermore, connecting these batteries to create a battery farm enables participation in wholesale and retail electricity markets. Various vehicles, including forklifts and ferries, can also benefit from this technology as a means of propulsion.

In addition to contributing to the development of a CE, these applications improve resource efficiency by optimizing material utilization. Given the increased complexity of the supply chain associated with these applications, it becomes crucial to establish a robust data system to monitor the movement of materials (Beer et al., 2012; Tong et al., 2013).
The automotive industry currently utilizes a wide range of materials in EV battery chemistry, with no standardized battery chemistry type developed. This is primarily because EV batteries are relatively new to the market, and manufacturers are still experimenting with different chemistry combinations to achieve the right balance between range and power, as well as gain a competitive edge. Factors such as price, availability, and potential environmental impact also play a role in selecting materials. Common materials found in current EV batteries include cobalt and graphite, both of which are classified as critical materials in the EU, indicating their significance in the EV market but potential scarcity to meet future demand. Scarcity can arise from geographical or geopolitical issues, price fluctuations, or ethical and environmental concerns (European Commission, 2018).

As the reliance on critical materials for EV batteries increases within the UK and the EU, transitioning from a linear economy to a circular one becomes increasingly important. A CE aims to keep resources in continuous use, extracting maximum value from them and minimizing waste. The metal components of EV batteries can be continuously recycled, fitting seamlessly into a CE model that allows resources to circulate through key lifecycle stages, reducing the need for virgin raw material extraction (Figure 1). Leasing EV batteries could further enhance their management after they are removed from vehicles, facilitating traceability, repair, and reuse, repurposing, and recycling. This approach reduces reliance on critical materials and promotes the development of a battery CE.

To maximize PV consumption, the Second Life Batteries can be utilized as a solar battery, supply demand-side flexibility, and even be aggregated to supply utility-scale storage. In this work, we examine the results of a focus on optimal EV battery utilization over the course of the battery's whole life. The study is performed from the point of view of the EV owner, and the savings in energy and money are calculated by optimizing the battery's economic use over its entire lifetime. An MILP (mixed integer linear programming) optimization algorithm is built in two stages to calculate the lifetime value of EV batteries. The first step is to maximize the EV's battery life, and the second step is to recycle the same battery for another EV. The second stage of the MILP algorithm optimizes SLB usage in the home. The following is the outline for the paper: Methods are discussed in Section 3 after the literature is covered in Section 2. Part 4 contains the findings and discussion, while Section 5 provides the summary and final thoughts.

1.4 Research Rationale

EVs with strong storage systems can help to reduce our reliance on fossil fuels and improve air quality. Strong storage systems can also help to extend the range of EVs, making them more practical for everyday use. (Curry, 2021) Concerns have been raised about the sustainable disposal of LIBs, which are included in EVs and contain precious components as well as environmental risks, as the EV market continues to expand rapidly. To solve this problem, we need to adopt the principles of the CE that is closing the loop, which prioritize recycling and reuse of materials.

Battery packs that have reached the end of their lifespan in EVs but still retain a significant amount of energy storage capacity can be effectively repurposed in fixed residential storage systems. This approach provides a sustainable solution to address the challenge of handling spent EV batteries. Instead of disposing of these batteries, they can be utilized in stationary storage applications, allowing homeowners to store and utilize renewable energy efficiently.

By integrating retired EV batteries into residential storage systems, the energy storage capacity of these batteries can be harnessed, extending their useful life, and maximizing their value. This approach not only reduces the environmental impact associated with battery disposal but also enables the efficient utilization of energy generated from renewable sources such as solar power

Some businesses have initiated pilot projects to investigate the feasibility of recycling batteries for use in stationary energy storage. Yet, there is an absence. of studies examining the viability and efficiency of reusing EV batteries in stationary household storage systems as a CE approach for dealing with used EV batteries. The technical, economic, environmental, and policy elements that affect the viability and efficacy of this strategy must be identified, which is why this study is necessary.

1.5 Research Objectives

The objectives of this study are:

1. To check the feasibility of used batteries as a long-term option for EV battery reuse.
2. To calculate the potential cost along with benefits of reusing batteries in household storage applications.

3. To highlight the technical issues like performance variability and safety considerations related to utilize recycled batteries in stationary storage devices.
4. To analyze the reliability of reusing EV batteries in stationary storage systems, e-bikes and reefers us to aid in the shift to a sustainable energy infrastructure.

1.6 Problem Statement

Amidst the escalating adoption of EVs in Pakistan, the pressing issue of sustainable battery management arises, necessitating efficient approaches for disposal, recycling, or reuse. Disposing of these batteries without proper consideration poses a significant environmental burden and squanders valuable resources. Evaluating the cost-effectiveness of battery reuse becomes crucial, given the challenges faced by developing countries. Hence, this study aims to conduct a Comprehensive CBA to assess the feasibility of a sustainable solution for minimizing EV waste by exploring various applications of battery reuse.

1.7 Circular Economy and Reuse of EV Batteries

The concept of CE holds significant importance in today's world as it offers a sustainable alternative to the traditional linear "take-make-dispose" model of production and consumption. CE aims to maximize the value and utility of resources by promoting the reuse, refurbishment, and recycling of products, thereby minimizing waste generation and environmental impacts. One crucial aspect of CE is the application of reusing products, which has several notable benefits (Ellen Mac Arthur Foundation, 2014).

Firstly, reusing products helps conserve natural resources. Through product reuse, the necessity for extracting and processing raw materials is diminished, as the lifespan of products is extended. This, in turn, alleviates the pressure on ecosystems and reduces the energy consumption associated with resource extraction and manufacturing. Secondly, reusing products contributes to waste reduction. When items are reused, they are prevented from becoming waste or ending up in landfills. This reduces the strain on waste management systems, mitigates pollution risks, and minimizes the release of harmful substances into the environment. Thirdly, reusing products can lead to economic benefits. The practice of reusing products fosters job creation and stimulates economic activity in industries such as repair, refurbishment, and remanufacturing. It also provides affordable options for consumers, especially in sectors where new products may be financially out of reach for some individuals or communities (European Commission 2021)

Moreover, reusing products supports innovation and promotes sustainable design. When products are designed with reuse in mind, it encourages manufacturers to create durable, repairable, and modular items that can easily be disassembled, and components reused or upgraded. This shift towards a more circular design approach drives innovation, stimulates creativity, and fosters the development of eco-friendly solutions (Patrick, 2018).

Additionally, reusing products can have positive social impacts. It enables the redistribution of goods to individuals or communities that may not have access to new items, thus promoting equity and reducing inequality. (Anita. 2022) said that Reuse initiatives, such as community sharing platforms or second-hand markets, can also foster social connections and promote a sense of community.

The application of reusing products within the framework of CE is highly significant. It contributes to the conservation of resources, waste reduction, economic growth, sustainable design, and social well-being. By embracing and expanding reuse practices, we can move towards a more sustainable and resource-efficient society (Gabi, 2023).

Numerous companies are increasingly integrating CE principles into their business models or making commitments to do so within a specified timeframe. An illustration of this is seen through partnerships between major companies such as Nike and IKEA with DyeCoo, a company that applies sustainable practices in the textile industry notorious for generating significant amounts of toxic waste. DyeCoo employs their patented technology, utilizing CO2 instead of water, employing pure dyes, reusing dye, eliminating processed chemicals, and prioritizing energy efficiency (Arindam Basu, 2020).

Furthermore, the CE has made inroads into the air travel sector as well. Several airline companies have devised innovative approaches to repurpose, refurbish, and recycle retired aircraft components. Considering that over the next decade, a staggering 11,000 aircraft are anticipated to be retired, up to 90 percent of these aircraft parts can be effectively reused. This noteworthy development represents a significant stride towards embracing the CE mindset and its principles.

There have been numerous obstacles hindering the transition to renewable energy (IRENA, 2021-2022). Economic barriers, such as subsidies for non-renewable energy and low oil prices discouraging renewable investments, have impeded progress. Social challenges have also played a role, with public concerns about changes to local landscapes and disruptions to established ways of life (European Commission, 2021). However, international pressure and growing awareness of the detrimental effects of fossil fuel-based energy are driving government initiatives to decarbonize the energy sector. Examples include the European Union's European Green Deal, which aims for net zero greenhouse gas emissions by 2050, and China's commitment to achieving carbon neutrality by 2060 (European Commission, 2021).

1.8 Contribution

The research constitutes a substantial academic contribution aimed at comprehensively addressing the imperative of sustainable battery utilization within Pakistan's burgeoning electric mobility landscape. This study's distinctiveness emanates from its adept synthesis of theoretical underpinnings, methodological precision, and empirical insights, yielding a profound understanding of the circular economy's potential and strategic reintegration of second-life electric vehicle (EV) batteries.

Pioneering Circular Economy Framework:

The research's academic innovation resides in its pioneering lens of a circular economy framework applied to battery reuse within the Pakistani market. In an era that demands transcending traditional linear consumption models, this approach envisions batteries as resilient assets undergoing multiple life cycles. This scholarly departure underscores the study's theoretical innovation by contextualizing global sustainability paradigms within the intricate contours of Pakistan's nascent EV ecosystem.

Strategic Infrastructure Preemption:

Positioned at the crossroads of government incentives propelling EV adoption and the escalating fuel costs, the research cogently underscores the imperative of pre-emptive infrastructure development. Its hallmark contribution lies in championing the strategic deployment of investments in EV infrastructure, strategically laying the groundwork for a robust battery reuse ecosystem. This strategic impetus augments resource efficiency, curtails costs, and ensures preparedness for the inevitable shift towards electric mobility.

Rigorous Economic Evaluation of Battery Scenarios:

At the crux of the research's empirical foundation lies a meticulous economic evaluation of three distinct second-life battery scenarios. This involves an intricate analysis utilizing critical financial metrics including the Internal Rate of Return (IRR), Payback Period, and Net Present Value (NPV). The calculated IRR offers insights into the viability of each scenario, the payback period quantifies the time required to recoup the initial investment, and the NPV captures the project's profitability by accounting for the time value of money. The judicious integration of these metrics exemplifies methodological rigor, emblematic of advanced research inquiry in battery reuse dynamics.

Policy Implications for Facilitating Sustainable Transition:

The research integrates empirical findings with the formulation of policy implications, bridging the chasm between academic inquiry and policy praxis. By advocating for a regulatory environment conducive to battery reuse, the research transcends theoretical discourse into actionable strategies. This contribution effectively ensures that empirical insights resonate within the practical sphere, engendering an environment primed for the seamless integration of second-life batteries across diverse sectors, thereby bolstering Pakistan's nascent circular economy.

Synergistic Intersection of Sustainability and Economics

Of particular significance is the research's endeavor to interlace the realms of sustainability and economics. By intertwining environmental facets such as carbon footprint reduction and energy efficiency gains with financial metrics, the study underscores the multifaceted nature of battery reuse's impact. This holistic integration underscores the interdisciplinarity essential for a sustainable transition within a developing nation's evolving mobility landscape.

Intellectual Trajectories for Future Research:

The research extends its contributions by identifying intellectual trajectories for future inquiries. These trajectories highlight potential knowledge gaps, avenues for refinement, and extensions within the discourse on battery reuse. This proactive orientation aligns with the essence of scholarly progress and dissemination of knowledge.

CHAPTER 2. LITERATURE REVIEW

Within this chapter, a comprehensive examination of the factors under investigation is presented. It establishes the theoretical framework by integrating relevant theories that substantiate this research and will be employed to interpret the findings. Furthermore, it outlines the hypotheses and conceptual models formulated specifically for the present study.

Pakistan is one of the most vulnerable countries to climate change. The average temperature and precipitation have been affected, and carbon dioxide from fossil fuels is harmful to human health. It can contribute to the spread of disease via contaminated floodwater. If no action is taken on climate change, the average temperature in Pakistan is expected to rise by 3 °C. (Carabine, 2014). Despite Pakistan's promises to reduce greenhouse gas emissions by approximately 20% by 2030 at the SAARC summit, there has been little effort to build and deploy electric cars in Pakistan. (Energy Centre and Dept, 2017). The economic situation in Pakistan is worsening, and environmental conditions are deteriorating at an alarming rate. These are major issues facing the country. If serious steps are not taken to address these growing risks, the situation could worsen in the coming years.

Pakistan urgently needs a comprehensive strategy to solve these huge problems. The transportation industry is responsible for most the country's greenhouse gas emissions. This has led to a rapid decline in Pakistan's air quality. Multiple environmental pollutants are present in concentrations more than ten times that of the WHO's upper limit. This situation is only set to worsen over time. (Rabi' al-Thani, 2019)
Air pollution has been linked with an increasing number of deaths and other illnesses. The mortality rate caused by environmental pollution far exceeds the rates of other well-known killers, such as malaria, tuberculosis, and HIV/AIDS. (Rabi' al-Thani, 2019)
The general population has suffered from air pollution, and the problem will only get worse. It is crucial to find a solution. EVs can help to solve these problems.
EVs do not produce emissions, which would help to improve air quality. They are also more efficient than gasoline-powered cars, which would help to reduce greenhouse gas emissions. (Rabi' al-Thani, 2019)

If Pakistan were to switch to EVs, it would make a significant contribution to the fight against climate change. It would also improve air quality and public health.

The GoP should take steps to promote the use of EVs. This could include providing subsidies for EVs, investing in charging infrastructure, and making it easier for people to purchase EVs.

By taking these steps, Pakistan can make a real difference in the fight against climate change and improve the lives of its citizens. Plug-in hybrid-electric vehicles (PHEVs) have emerged as a promising technology for reducing petroleum consumption in the vehicle fleet by utilizing electricity. However, the costs and benefits of PHEVs vary significantly depending on factors such as battery costs, fuel costs, vehicle performance attributes, and driving habits. This case study aims to compare the costs (vehicle purchase costs and energy costs) and benefits (reduced petroleum consumption) of PHEVs in relation to hybrid-electric and conventional vehicles. A detailed simulation model is employed to predict petroleum reductions and costs of different PHEV designs compared to a baseline midsize sedan. Two powertrain technology scenarios are considered to assess both near-term and long-term prospects of PHEVs.

The analysis reveals that PHEVs equipped with 20 miles (32 kilometers) or more of energy storage can achieve petroleum reductions exceeding 45% per vehicle. However, the long-term incremental costs of these vehicles are projected to exceed US$8,000, with near-term costs being considerably higher. An economic analysis demonstrates that high petroleum prices and low battery costs are necessary to establish a compelling business case for PHEVs in the absence of other incentives. Nonetheless, considering the significant potential for petroleum reduction, there is a strong rationale for government support to accelerate the deployment of PHEV technology.

The EVs are powered by batteries, primarily utilizing lithium-based technologies (Scrosati & Garche, 2010). Like many other items, batteries undergo degradation with usage (Broussely et al., 2005). In the case of traction use, batteries are generally considered unsuitable once they have lost approximately 20 to 30% of their capacity or power. At this stage, they should be removed from the vehicle and typically collected for recycling.

European directives have been introduced to enforce the collection of battery and accumulator waste by imposing recycling costs on battery manufacturers (Directive 2006/66/EC) and setting a collection target of at least 45% of batteries sold by 2016. However, achieving this target has proven challenging due to the inefficient collection network for small batteries on the market and the integration of batteries into various appliances (Weyhe, 2013).

It is important to note that EV batteries are not subject to the same directive, and the responsibility for their recovery and recycling falls upon car manufacturers. Car manufacturers are expected to recycle up to 85% of the car's weight and recover an additional 10% of the weight energetically. Therefore, it is crucial not to lose any batteries after their car-life, despite the current high costs of recycling batteries (Lithorec, 2012).

There is an alternative approach to recycling. Even if EV batteries no longer perform optimally compared to new ones, they are still in relatively good condition compared to average energy storage systems used in stationary applications. As a result, there might be some economic and practical value in extracting further use from them before recycling. Second-life applications could enhance deposition and control, as the owners have something to gain. Additionally, second-life use may slightly reduce EV prices and increase their appeal compared to ICE, contributing to cost reduction efforts (Canals, Amante, & González, 2014).

Furthermore, reusing batteries could potentially lead to lower battery prices for stationary grid applications, facilitating the implementation of micro-grids, decentralized energy production, and the integration of smart grids with their associated benefits (Roberts & Sandberg, 2011), (Eyer & Corey, 2010). Finally, reusing second-life EV batteries directly contributes to a reduction in environmental impact (Ciccioni et al., 2012). By promoting reuse, the manufacturing of new batteries can be reduced.

While the concept of second-life reuse is promising, it is not a straightforward process. Batteries need to be collected, inspected, tested, and prepared as necessary. Their state of health (SOH) must be evaluated, and they should be classified and stored until the second-life installation is ready. All of these battery-related tasks involve costs. Subtracting these costs from the income and profit generated by second-life applications determines the "willing to pay" value for these used batteries. If this value is sufficiently high, the positive aspects can continue to be realized.

However, if the value is too low or negative, the prospects are limited. The number of transportation-related V2G (vehicle-to-grid) applications is increasing. Electric motor fleets can be utilized during the day even while they are parked by pooling resources for secondary functions (Calvillo et al., 2016a). Active participation from end users is crucial for improving macroeconomic management, and V2G enables this possibility (DSM). There is a growing interest in using electric cars (EVs) as a renewable energy source for homes, leading to the development of innovative applications like V2H (Goncalves, 2018). The objective is to utilize

V2G to enhance building consumption through distributed source management (DSM) capabilities (Buonomano, 2020).

Whether an electric car can be used as a storage device depends entirely on the driver. Driving patterns can be broadly categorized as systematic or unsystematic. While the "systematic pattern" involves commuting between home and the office, the "unsystematic mobility pattern" includes trips to stores, accounting for a third of all journeys. Six European Union (EU) countries, namely Italy, Europe, Germany, Great Britain, Spain, and Croatia, account for 35-40% of all visits (Pasaoglu et al., 2014). According to researchers, experimenting, testing, and sharing tacit knowledge contribute to the widespread acceptance of V2G in Nordic nations (Noel et al., 2021). A report examining the effects of V2G on China's renewable energy goals for 2030 found that increasing wind power generation by 6.6% and decreasing solar power generation by 3.8% could reduce the system's overall cost by at least 2% (Yao et al., 2022). Synchronizing solar cells (PV) and alternative fuels in multifamily buildings using real-time pricing has been shown to reduce expenses (Seyyedeh Barhagh et al., 2020). Several studies have examined the benefits of V2B and developed new algorithms and assessment methodologies applicable to various building types and management system scenarios (Heredia et al., 2020; Barone et al., 2019). By paying more attention to potential partnerships with EV and facility operators, energy savings in buildings can be achieved through the utilization of EVs (Tanguy et al., 2016).

2.1 Lifespan of a Reused Battery

The lifespan of a battery used in an electric car is influenced by multiple factors (temperature, usage hours, and recharge cycle) including the frequency and depth of charging, discharging, and energy draw. According to (Michele, 2017) when the battery's capacity drops by 20%, its negative effects on the vehicle's speed, range, and regeneration make it unsuitable for use. Extending the useful life of the battery is essential for the CE due to the potential reductions in material consumption, mining impacts, and greenhouse gas (GHG) emissions. The goal is to harness the potential of an inclusive business model that emphasizes repair, reuse, and recycling. Given the challenges associated with battery recycling, prolonging their service life can significantly contribute to the development of a sustainable society. The SLB which costs a fraction of conventional batteries, is well-suited for a specific segment of the stationary storage market. By 2025, over 75% of EV batteries will have been reused at least once before being recycled (Michele, 2017) Second-life batteries are currently being used and studied in various personal, commercial, and industrial applications. Case studies are being conducted to explore specialized uses such as the storage of renewable electricity in Ljubljana (Pagliaro and Meneguzzo, 2019), demonstrating the potential of these batteries. The profitability of domestic storage might not be the most lucrative market, considering the increased profitability of grid support services (Martinez-Laserna et al., 2018). The flexibility of batteries allows for the provision of services like demand response management and maximizing the use of rooftop PV systems. However, the intermittent nature of supply and demand in mountainous PV installations can lead to inefficiencies. Excess locally generated power during times of low demand goes unused, making grid management more challenging as PV installations become more widespread. One solution is to maximize personal consumption, and in some European Union (EU) countries, homeowners can even sell their surplus power to the grid for a small profit. This has led to the growing popularity of PV systems integrated with battery storage. Second-life rechargeable batteries offer a potential solution to the high cost of LIBs, which has hindered the adoption of this strategy. The applications only scratch the surface of their potential; they can also assist with maximum demand control, peak shaving, and load leveling. The figure 5 shows the number of cycles and life of the battery in first life, second life and end of life.

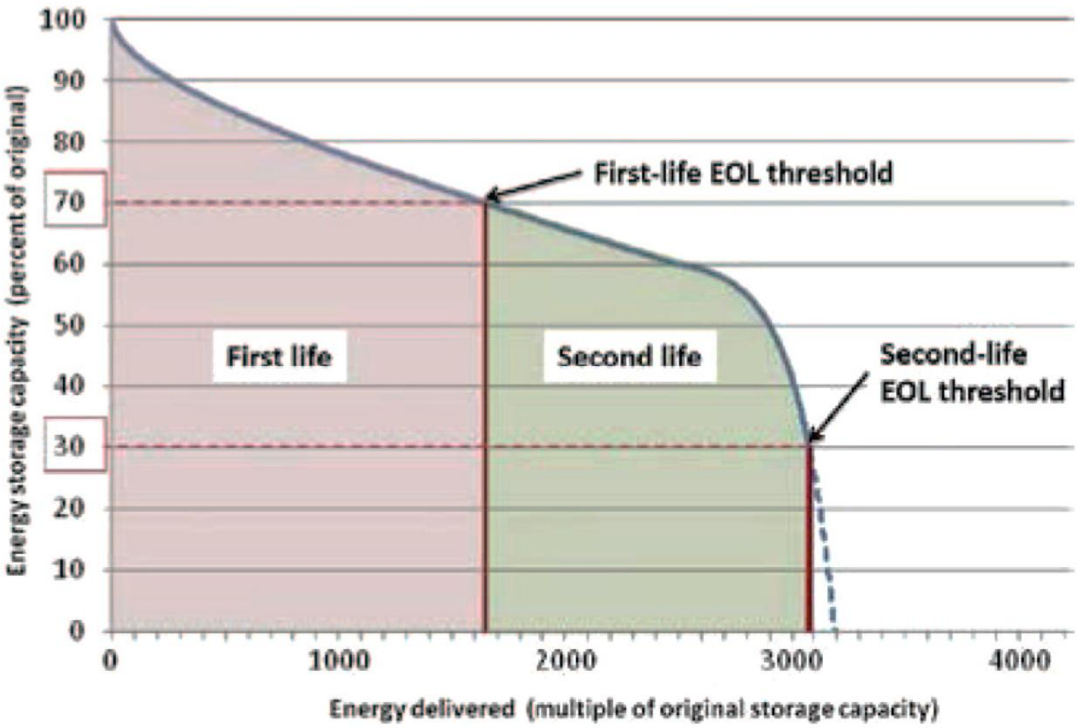

Figure 5 Life of li-ion EV Battery (Locorotondo, E. et. al, 2020)

2.2 Potential of Second Life Batteries

A study was conducted to evaluate the potential of second-life batteries in the construction industry. By extending their usage over longer periods, battery life can be increased by up to 35%, and there may be financial benefits in markets where aggregator-based demand response programs are implemented (Canals Casals et al., 2019a). Another study focused on determining the optimal size of a Battery Energy Storage System (BESS) for a PV-powered virtually net-zero-energy building. Incorporating second-life batteries for storage and evaluating their potential for environmental sustainability could demonstrate the ecological advantages of reusing batteries in structures (Cusenza et al., 2019). In a separate investigation, an energy storage system equipped with second-life batteries was installed in a Portuguese home, and it was found that batteries offered both technological and financial advantages (Assunço et al., 2016).

Various evaluations have been conducted to determine the ideal charging approach for EVs, aiming to minimize charging costs while considering the anticipated costs associated with battery degradation. Hoke et al. developed a simple battery longevity model that optimizes charging costs while accounting for expected battery degradation costs (Hoke et al., 2014). Neubauer et al. considered the cost of different battery electric vehicle (BEV) charging strategies and developed a battery incentive structure along with a detailed battery degradation simulation (Neubauer et al., 2012).

Frequency regulation is often a focal point in research on EV fleets. Scarabaggio et al. introduced novel control procedures for EV battery control during load frequency control services, addressing the needs of EVs during charging while ensuring power rebalancing and grid stability (Scarabaggio et al., 2020). Congestion management was also examined in the context of a control approach for Li-ion battery storage participating in grid power networks (Yan et al., 2018). Uncertainty arising from distributed energy resources like wind and photovoltaics has led to the development of models to accommodate these factors (Sperstad and Korps, 2019).

Category	Application	Functions	Reference
Stationary Storage (National Level)	Centralized Power Station	Renewable energy integration, smoothing control, reducing curtailed electricity	Weber, L. et. al, 2013 Rodriguez, P. et. al, 2015 Fitzpatrick, A. et. al 2023
Stationary Storage (Domestic Level)	Transmission and Distribution Network	Alleviate grid congestion, offer ancillary support to the network, and delay the expansion of power transmission and distribution capacity	Smith, K. et. al 2015
Consumer Focused	Communication Bases Industrial EV Chargers Mobile Energy Storage devices Low speed Electric Vehicle Streetlights Residential Energy Storage	Backup Power Storage Community EV Charging Power Supply for Reefers and Camping Trailer E-Bikes Energy Storage for road lamps Emergency Power Emergency Power Reduce electricity costs	Yan, Z. et. al 2019 Kamath, D. et. al 2020 Alexander, L. et. al 2019 Zhu, M. et. al 2020

2.3 Energy Storage Medium

Studies are being conducted to assess the practicality of using second-life batteries as energy storage mediums. Their suitability for intelligent buildings has also been investigated, showing that if utilized to meet building demands and participate in electricity markets, second-life batteries can remain economically viable for more than four years (Canals Casals et al., 2019b). In Portugal, a study examined the feasibility and cost-effectiveness of integrating second-life batteries with PV systems in a building.

Several research papers have focused on intelligent EV charging and the second life of batteries for demand-side management in buildings. However, the literature review revealed a knowledge gap regarding the comprehensive quantification of financial and energy savings throughout a battery's entire lifecycle, considering the various configurations used by EV users. To address this gap and considering the expected increase in used and discarded EV batteries in the coming decades, this study aimed to calculate the total energy and monetary savings achieved by an EV battery over its entire lifespan from the perspective of the vehicle owner.

2.4 Decarbonization of Transport Sector

The decarbonization of the transportation sector and the need to meet climate change targets necessitate the rapid growth of electric cars (EVs). However, this shift has increased the demand for critical battery materials, leading to supply chain constraints and security risks. On the other hand, when EV batteries are no longer useful, they can be recycled or reused. This study presents a material flow analysis (MFA) based on potential EV fleet scenarios, charger chemistry adjustments, and end-of-life methodologies to forecast future energy storage system waste generation and the requirements for key battery materials in Sweden. The study also applies MFA with a sociotechnical lens to explore how potential social and technological shifts in the future may impact energy storage technology recycling and the supporting infrastructure. The analysis predicts a peak in raw material demand around 2040-2050 under current trends, but recycling efforts could reduce this peak by 25 to 64 percent, indicating that waste materials could meet a significant portion of future needs. Second-life use of energy storage technologies can contribute to circularity, despite the delayed implementation of recycling options. This shift is crucial as it enables recycling promotion, second-life use of battery packs, and the advancement of energy technologies, which will require transformative changes in technology, markets, business practices, legislation, power grids, and user behavior. Specialized battery technologies may emerge to meet the demand for high-capacity batteries in grid decarbonization and other aviation applications. The importance of robust regulatory frameworks in fostering a closed EV battery value chain is emphasized in each potential outcome (Nurdiawati & Tarun Kumar Agrawal, 2022).

2.5 Reuse of EV Batteries

Regarding the literature on EV battery recycling at the end of their useful life, much of it focuses on recycling rates, economic benefits, and environmental impacts. China, in particular, faces challenges with a low return rate for used EV batteries. Unauthorized recycling channels, such as home-based repair companies, contribute to negative environmental effects (Hu and Yan, 2015; Gu et al., 2017). Improving the infrastructure of the end-of-life battery recycling network and enhancing recovery technologies are crucial to address car manufacturers' low enthusiasm for participating in recycling efforts (Zeng et al., 2015). The increasing repurchase price of batteries by local firms hinders consumer participation in organized recycling programs (He and Sun, 2022). Consumers' negative perceptions of recycling EV batteries at the end of their useful lives can be influenced by a chaotic recycling market, inadequate compensation, and improper recycling pathways (Dong and Ge, 2022). Repurposing end-of-life EV batteries for profit can be achieved through recovery use and cascade use. The financial gains from recycling the metals in EV batteries, such as lithium, nickel, copper, and cobalt, are significant (Babbitt et al., 2014; Kamath et al., 2020). Cascade applications must occur before material recovery to maximize economic efficiency (Omrani and Jannesari, 2019). (Jiang et al. 2021) found that cascade applications for energy production yield greater financial benefits than mechanical recycling alone when analyzing the costs and benefits of recycling end-of-life EV batteries in China.

The sustainability of the market for end-of-life (EOL) batteries for EVs is heavily influenced by government decisions within the existing governance structure. Many countries consider promoting the use of EVs as a regulatory reform to phase out fossil fuels. Effective recycling of EOL EV batteries is crucial for energy conservation and minimizing environmental damage. Several countries have implemented regulations and incentives to facilitate battery recycling from retired EVs. For instance, Japan has adopted regulations and provided subsidies to battery manufacturers to regulate battery recycling. In the United States, regulations and deposit schemes are used to encourage battery recycling. In Germany, the recycling fund law incentivizes battery manufacturers to collaborate and share recycling resources. Academic discussions on EOL EV battery governance often employ a behavioral economics approach. (Li & Mu ,2018) found that a recycling partnership in a three-tier lithium closed-loop supply chain can enhance customer enthusiasm for formal recycling by reducing recycling costs and improving pricing. (Tang et al. 2018) used a game model analysis and suggested that setting reasonable minimum recycling rates and enforcing criteria can effectively incentivize EV manufacturers to implement recycling. (Yang et al. 2021) used a system dynamics approach and found that government involvement mechanisms can better incentivize EV manufacturers to actively engage in recycling tasks compared to subsidized mechanisms for end-of-life electric drive batteries.

Lead acid battery pollution is often raised as a concern for regulating e-bikes. In China, approximately 95% of e-bikes rely on lead acid batteries, although this percentage is decreasing due to advancements in battery technologies (Jamerson & Benjamin, 2007). Interviews with manufacturers and service facilities indicate that the typical lifespan of an e-bike battery is 1-2 years or up to 10,000 kilometers (km). Bicycle-style e-bikes commonly use 36 V battery systems, weighing around 14 kilograms (kg) on average, while scooter-style e-bikes use 48 V battery systems weighing approximately 18 kg. Since lead accounts for 70% of the total weight of electric batteries, bicycle-style e-bike (BSEB) batteries contain 10.3 kg of lead, whereas scooter-style e-bike (SSEB) batteries contain 14.7 kg of lead.

The issue of lead pollution is a significant concern for e-bikes, and it has had similar repercussions on the electric car industry in the United States in the 1990s (Lave, Hendrickson, et al., 1995). Due to the relatively short lifespan of deep-discharge e-bike lead acid batteries, an e-bike may use up to five batteries during its lifetime, resulting in lead emissions into the environment with each battery replacement. Lead is released into the environment through mining and smelting of lead ore, battery manufacturing, recycling of used lead, and non-recycled lead disposal.

The lead acid battery system in the People's Republic of China (PRC) differs significantly from that of more industrialized countries (Roberts, 2006). Mao, Lu, et al. (2006) investigated the PRC's lead acid battery system and found that 16.2% of the lead content is lost during mining and concentrating, 7.2% is lost during primary smelting, 13.6% is lost during secondary smelting and recycling processes, and 4.4% is lost during battery manufacturing. These loss rates are calculated based on the final battery production rather than the initial lead input. For example, 1 ton of final lead output represents a loss of 0.044 tons during battery manufacturing. Figure 1.1, derived from the analysis by Mao, Lu, et al. (2006), illustrates these high loss rates, primarily attributed to poor ore quality and the utilization of outdated technology in small-scale factories for lead refinement. The official lead recycling rate in the PRC's lead acid battery industry is reported as 31.2%, but Mao, Lu, et al. (2006) estimate the actual rate to be approximately double that, accounting for unreported recovery by informal, small-scale recyclers. Given the high value of lead, it is projected that the overall recycling rate exceeds 85%, and with the recent tripling of lead prices, the recycling rates may approach 100%. The lead recycling rate plays a role in determining the proportion of recycled lead in each battery.

The data utilized by Mao et al. (2006) are from 1999, prior to e-bike batteries becoming a significant market share. Some values, particularly the recycling rate, are estimates and could have changed since the introduction of e-bikes. As e-bikes have surpassed the total number of cars, they now represent a substantial portion of lead acid battery production. Due to the rapid battery consumption of e-bikes, informal recycling and collection practices have emerged. Typically, e-bike customers can exchange their depleted batteries for a new one at a reduced price, often around CNY100 ($14.30) in 2008, which is a significant amount in most PRC cities. The used batteries are then collected from service centers and directed to formal and informal lead recycling facilities. This practice has the potential to increase the overall recycling rate of lead acid batteries. Interviews with factory owners indicate that an estimated 85% to 100% of e-bike batteries are recycled (references needed). Recycling practices and technology have also witnessed significant improvements, with the PRC developing environmentally friendly lead smelting technologies as alternatives to traditional methods.

E-bikes offer the convenience of recharging by plugging into standard wall outlets, eliminating the need for dedicated refueling or recharging infrastructure. Many e-bikes feature removable batteries and chargers, allowing users to transport them to apartments or workplaces for recharging during the day or night. With the growing popularity of e-bikes, several apartments and workplaces are retrofitting bicycle parking areas to accommodate e-bikes by providing electrical outlets.

The charging time for e-bike batteries typically ranges from 6 to 8 hours. Charging e-bikes at night can enhance the efficiency of the electric power generation network. Excess electricity production capacity can be utilized to charge batteries during off-peak hours, effectively smoothing the demand peak and potentially eliminating the need for additional electricity generation capacity. While e-bikes produce zero tailpipe emissions, they rely on electricity, which is generated using conventional processes that emit significant amounts of pollutants and greenhouse gases.

On a single charge, most e-bikes can travel approximately 40 to 50 km. Considering a standard scooter-style e-bike with a 350-watt motor and a 48 V, 14 amp-hour battery, the electricity requirement is estimated to be around 1.5 kWh per 100 km. Accounting for efficiency losses in the battery charger, the actual electricity consumption from the wall outlet could be around 1.8 kWh per 100 km. Additionally, transmission losses and in-plant use losses account for about 12% to 14% of the total energy produced. As a result, the electricity generation requirement for a typical e-bike is approximately 2.1 kWh per 100 km. Some estimates suggest that transmission loss rates may be twice as high as officially reported. In the PRC, the energy mix consists of 75% coal, 15% hydro, 8% gas, and 2% nuclear power. Figure 1.2 provides the emission factors of typical power plants.

It's important to note that the energy mix in each city within the PRC depends on its specific region. The country is divided into 15 power grids with varying levels of connectivity. Each grid has a distinct energy mix, and cities receive most of their electricity from the grid in which they are located.

2.6 Barriers to E-bike Adoption

Initial purchase cost

E-bikes are typically priced higher than traditional bikes, with a price difference of approximately 25-40%. The findings from the CRD survey indicate that 37% of respondents view the cost of e-bikes as a significant barrier to adoption. Interestingly, a study showed that individuals who had the opportunity to test ride an e-bike exhibited a much greater willingness to pay for one (Reference 9). This suggests that providing opportunities for community members to engage with e-bikes could potentially increase their uptake within a community.

Lack of secure bike parking and end-of-trip facilities

Concerns regarding e-bike theft present another barrier to ownership, which can be partly attributed to the lack of secure bike parking options within communities. The CRD survey highlights that 42% of public respondents consider this issue to be critical, necessitating policy attention. Additionally, some e-bike owners encounter difficulties in finding bike stands that are large enough to accommodate their e-bikes, as well as parking facilities that provide charging options. Similar to the challenges faced with EV charging in multi-unit residential buildings (MURBs), there is often a shortage of electrical outlets near bike storage areas in MURBs. Furthermore, the absence of end-of-trip facilities equipped with showers and lockers can discourage potential cyclists from adopting e-bikes. (References needed for CRD survey and additional studies)

2.7 Use of Batteries in Reefer Containers

At the vehicle level, EVs offer several advantages for urban freight transport (UFT), including potentially lower operating costs, zero tailpipe emissions, the potential to be fossil-fuel free, quieter operation at low speeds, and higher energy efficiency (Wang et al., 2018). However, the widespread adoption of this technology remains relatively modest (Moultak et al., 2017). The main drawbacks of EVs compared to traditional ICEVs are attributed to the current battery's lower energy performance relative to fossil fuels. The combination of heavy, large, and expensive batteries, along with the relatively slow recharging process, significantly constrains operational performance in terms of driving range, available operation time, payload capacity, and increases the price of EVs (Duarte et al., 2016). Furthermore, the existing ecosystem that supports ICEV-based transport is resistant to the transition to EV-based freight transport. Essential components such as a diverse vehicle market, public fast charging infrastructure networks, repair and maintenance services, and roadside assistance services are either absent or scarce even in developed cities worldwide (International Energy Agency, 2018). As governments need to carefully design policies to incentivize electric mobility (Philipsen et al., 2019), fleet operators must also consider their options for transitioning (Wang et al., 2018). Evaluation studies play a crucial role in this context. These studies focus on various aspects such as policy impacts on EV adoption, energy security, grid stability, air quality, greenhouse gas emissions, human health, planning and efficacy of charging infrastructure, potential user behavior, and cost calculations for individual companies (Daina et al., 2017; Requia et al., 2018; Sun et al., 2015; Wolbertus et al., 2018; Davis and Figliozzi, 2013; Duarte et al., 2016; Macharis et al., 2007; Teoh et al., 2018). Despite extensive research in this field, the study of refrigeration and EVs remains limited, despite the importance of Hotel, Restaurant, and Catering logistics, the remarkable growth of grocery home deliveries, the significant contribution of food transport to GHG emissions in the UK, the large number of refrigerated vehicles worldwide, and the adoption of EVs in food logistics services (Wang et al., 2018; Visser et al., 2014; Garnett, 2011; Chatzidakis and Chatzidakis, 2004; Balm et al., 2018). There is significant potential for decarbonization in transport, and further study is warranted. Temperature control represents a significant drain on the limited battery capacity of EVs, impacting the battery capacity requirement and vehicle operating performance. Energy consumption is influenced by factors such as the type of refrigeration equipment, cargo box size, amount of goods, and the temperature difference between the optimum and ambient temperature (Rai and Tassou, 2017). Additionally, energy consumption continues even when the vehicle is temporarily parked or idling, in contrast to non-refrigerated vehicles where energy consumption stops during idle periods. This aspect contradicts one of the usual benefits of EVs compared to ICEVs, where idling is virtually emissions-free (Gaines et al., 2006).

2.8 Evolutionary Game Theory (EGT)

This Theory was initially employed in biology, examines how social behavior evolves over time when individuals have limited information. In the 1960s, EGT was adopted by ecologists to understand complex ecological problems. Recently, EGT has been applied to economic and management strategy challenges, including those related to recycling. Researchers such as Debnath et al. (2018), Zhang et al. (2019), and Yang et al. (2019) have utilized EGT to study various aspects of recycling and management strategies. The packaging sector, for example, involves different participants employing diverse tactics in various contexts. EGT has also been used to investigate recycling incentives, oversight, construction waste disposal cooperation, and stakeholder participation strategies in waste electrical and electronic equipment (WEEE) reprocessing (Long et al., 2019; Ma and Zhang, 2020; Du et al., 2020; Shao et al., 2022; Wang et al., 2019; Wang et al., 2021).

This study aims to utilize an evolutionary game technique and numerical simulation to investigate the strategies employed by three key parties involved in the recycling of dead batteries from EVs: electric vehicle manufacturers, consumers, and the government. The transition towards widespread EV usage is crucial for decarbonizing the transportation sector and reducing greenhouse gas emissions. A study titled "How technology, recycling, and policy can mitigate supply risks to the long-term transition to zero-emission vehicles" by Slowik et al. (2020) projects a significant increase in the number of EVs on the road, from 2.4 million in 2020 to 81 million by 2050. It is estimated that over half of all newly purchased cars will be battery-electric variants by 2020. However, the handling of end-of-life EV batteries, which contain various chemicals posing risks to human health and the environment, presents challenges compared to conventional vehicles.

Understanding the potential risks associated with the transition to EVs in the Global South requires an examination of international vehicle flows, waste treatment challenges for end-of-life BEVs and their batteries (LIBs), the health and environmental impacts of LIB disposal, as well as the relevant legislation and practices throughout the e-vehicle lifecycle. The study recommends the development of science-based regulations to address regulatory gaps in the global trade of used hybrid cars, prevent the transfer of pollutants, and ensure a sustainable transition to e-mobility in Global South countries. In summary, effective management of end-of-life EVs and their components, along with the establishment of sound laws and regulations, are crucial for achieving a global CE and sustainable transformation towards e-mobility in both local and international contexts.

Battery cells powered by lithium-ion technology have gained prominence in the future transportation sector due to their minimal environmental impact and potential for savings. However, the management costs of LIBs have remained linear. To mitigate the economic and environmental consequences of metal mining, biodiversity loss, and improper disposal, this research explores the current and future state of sustainable materials, collection and disposal infrastructure, reuse possibilities, and regulatory requirements for LIBs in the United States. The study incorporates a literature review on end-of-life management and provides policy, institutional, and technical recommendations to enhance the state of the art in the US.

Automakers' EV plans are surpassing government goals as they aim to sell more than 20 million vehicles worldwide annually by 2025, a significant increase from the 2 million vehicle sales in 2019 (Slowik, Lutsey, & Hsu, 2020). Initially, EVs had high development costs and were produced in limited quantities. However, with the projected increase in volume to tens of millions of units per year, there will be a competitive battery supply and production at scale. Currently, five battery suppliers are already providing batteries for at least 200,000 EVs annually (Sharpe et al., 2020), and ongoing technological advancements include the development of chemistries that reduce the reliance on expensive materials, improved material utilization for higher production yield, increased energy density, and larger-scale production (CATARC, 2019; Chung, Elgqvist, & Sannhanagopalan, 2016).

China's EV goals play a significant role in driving global EV volume due to its market size, global auto industry interest, and dedicated policy efforts. During China's first phase of NEV regulations (2019-2020), the electric share of new passenger vehicle sales increased from 4.5% in 2018 to 5.3% in 2019 and reached 6% in 2020 (Cui, Hall, & Lutsey, 2020; EV-volumes, 2021). China introduced its second phase of NEV regulations in June 2020, which could further increase EV penetration to 10%-12% of new sales or more by 2023 (Ministry of Industry and Information Technology [MIIT], 2020). The official target set by China's State Council's New Energy Vehicle Industrial Development Plan 2021-2035, released in November 2020, is to achieve a 20% electric share of new vehicle sales by 2025 (China State Council, 2020). Moreover, the recently published Energy-saving and New Energy Vehicle Technology Roadmap 2.0, prepared by the Society of Automotive Engineering (SAE) China under the guidance of MIIT, proposes unofficial targets of approximately 40% new vehicle electric share by 2030 and over 50% by 2035 (SAE China, 2020).

In 2019 battery costs and technical specifications were characterized by multiple sources. The analysis considers the battery pack cost incurred by vehicle manufacturers, including battery production cost, and associated indirect costs to the supplier. According to global industry surveys, the sales-weighted average battery pack-level costs were around $156 per kWh in 2019 and decreased to $137 per kWh in 2020 (Bloomberg New Energy Finance, 2020, 2021). U.S. and Europe-based automaker battery packs produced for 100,000 EVs per year had an average cost of $175 per kWh in 2019-2020, with a pack-level energy density ranging from 325 to 350 watt-hour per liter (Wh/L) and a specific energy density of 150-170 Wh per kilogram (Wh/kg) (Anderman, 2019). These figures align with the cost estimates provided by automakers transitioning to higher production volumes, such as General Motors, Tesla, and Volkswagen, which indicated cell-level battery costs of approximately $95-$110 per kWh from 2019 to 2021 (Davies, 2017; Ewing, 2019; P3, 2020; Witter, 2018).

Advancements in cathode, anode, and cell design continue to drive the evolution of automotive LIBs. In terms of the total battery capacity in new passenger EVs sold globally in 2019, nickel-manganese-cobalt (NMC) technology accounted for over 60% of the market, while nickel-cobalt-aluminum (NCA) technology, mainly used in Tesla vehicles, represented around 30% (EV-volumes, 2021). Lithium-iron-phosphate (LFP) and lithium-manganese-oxide (LMO) technologies were also prevalent, with LFP technology being particularly developed and deployed in China. There has been a general trend towards higher nickel content, reduced manganese and cobalt content (e.g., NMC111 to NMC611), and increased specific energy and energy density. NCA and NMC batteries are typically employed in longer-range vehicles, while LFP is more common in shorter-range vehicles that require more frequent charging.

(EVs) and their end-of-life batteries can be valuable sources of secondary natural resources, but they also pose potential threats to human and environmental health. Understanding the composition of EVs and their batteries is crucial for ensuring proper recovery, reuse, recycling, and assessing the potential implications of their disposal.

EVs come in various layouts and types, such as Fuel Cell Electric Vehicles (FCEV), PHEV and BEV rely solely on electric motors powered by batteries, which can weigh several hundred kilograms due to the inclusion of numerous individual parts (Bobba et al., 2018). HEVs merge the advantages of ICE and electric powertrains. PHEVs can charge their batteries from the grid and use the electric propulsion system over longer distances, while Mild Hybrid Vehicles) primarily recover fuel during braking. FCEVs use fuel cells to power the electric motor instead of batteries or ultracapacitors (Assunção et al., 2016).

The composition of vehicles is constantly changing due to the increasing prevalence of electric and electronic components and ongoing battery technology development. This poses challenges for designing recycling and recovery strategies for essential materials found in End-of-Life Vehicles (ELVs) due to a lack of knowledge about the makeup of electric and electronic wastes (Abdelbaky et al., 2021).

Currently, EVs have a range of rechargeable batteries and chemistries to choose from. Comparative studies have shown that LIBs are superior to lead-acid, copper, and nickel-metal hydride batteries in terms of performance. LIBs, known for their increased energy density, are well-suited for use in automobiles. They offer advantages such as higher cell voltage, no maintenance needs, and lower self-discharge rates when not in use. LIBs have become the industry standard in EVs, comprising most of the EV battery industry from 2010 to 2019 (Neubauer et al., 2015).

Despite their advantages, LIBs have some shortcomings, including the risk of spontaneous combustion in response to heat and pressure, the use of hazardous and rare materials, decreasing costs but still relatively high, and relatively large size and density when used in EVs.

Battery composition may vary between manufacturers, even for the same type of battery. The weight of batteries in subcompacts, compacts, large sedans, and SUVs can range from over 200 kg to over 500 kg, indicating high concentrations of lithium and other resources (Neubauer et al., 2015) . The trend towards offering a wide variety of vehicle types aligns with the observed increase in battery weight.

The adoption of low-energy technologies is expected to drive a significant increase in demand for lithium and cobalt, with a projected 965 percent and 585 percent increase in demand, respectively, by 2050 compared to 2017 production rates (Curry, 2017). To prevent the potential burial of these materials in landfills or dumpsites, it is crucial to establish pathways for their collection and recycling to reduce the need for material extraction.

2.9 Issues in Waste Control

The increasing use of EVs is expected to result in a surge in the generation of waste batteries. Predictions indicate that the industry will produce around 0.8 million tons of waste batteries by 2027, and between 0.33 and 4 million tons of end-of-life LIBs generated by EVs will reach their end-of-life between 2015 and 2040. The improper management of this waste poses sustainability challenges for the transition towards electric mobility.

The waste management chain for retired automobiles involves multiple participants and intermediaries, including vehicle owners, recycling centers, dismantling facilities, grinders, recycling units, remanufacturing plants, second-hand marketplaces, and industrial landfills. To establish an effective closed-loop system, active participation, and cooperation from all these parties are necessary (Moyer, 2020).

The waste management hierarchy, established by the European Council Directive 75/442/EEC, emphasizes reduction (prevention), reuse, recycling, recovery, and disposal. To minimize waste generation, efforts should focus on reducing planned obsolescence in the EV industry, as the rapid evolution of technology, especially software updates, can contribute to increased obsolescence.

To facilitate reuse, safe recycling, and minimal disposal, EVs and their components must be designed in a way that allows for easy disassembly, distinct labeling and classification of components and materials, and consistency in shape and structure. Some proposals, such as "battery passports," aim to provide recyclers with detailed information about battery cells and packaging. However, designing comprehensive governance to encompass all future battery types poses significant challenges due to the rapid development and evolving composition of LIBs (Zhang,2018).

Efficient waste management requires the collection of EoL EVs and their component parts. However, the collection rates for EoL LIBs in North America and the European Union have been relatively low, with only around 5% and less than 20% of EoL LIBs collected in 2016, respectively (Zhang,2018).. Enhancing collection rates is crucial for ensuring the sustainability of subsequent waste management practices, but more research is needed to address this issue.

Considerable research has been conducted on reuse and recycling opportunities for EoL LIBs, exploring topics such as depreciation processes, the impact of materials on battery degradation, environmental factors, charging frequency, driving style, and the aging patterns of LIBs in different types of EVs. Understanding these factors is vital for efficient waste management and ensuring the safety of second-life batteries.

Overall, addressing the challenges posed by the increasing amount of waste generated by EVs requires active collaboration among stakeholders, effective waste management strategies, reduction of waste generation through design improvements, and a comprehensive approach that considers collection, reuse, recycling, and disposal stages. (Moyer, 2020) Recycling of end-of-life EV batteries can be carried out through various methods, including direct reuse, module disassembly, and cell-level recycling. Breaking down batteries to the cellular level allows for the most adaptable reuse, but it is also the most expensive due to the need for technological development, testing, and implementation of new control systems. EoL LIBs can find potential applications in large-scale electricity and grid distribution, as well as medium- and small-scale installations for energy management, power reliability, and transportation in both developed and developing countries. (Martinez-bolanos.2021)

Recycling EV batteries in the Global South offers several advantages, such as reduced reliance on foreign battery manufacturing, increased local employment rates, lower battery production prices, and reduced battery replacement costs (Moyer, 2020). However, there are challenges associated with recycling EV batteries, including the wide variety of battery types, chemistries, and designs, the lack of comprehensive solutions for recycling, and the preference for new batteries over recycled ones.

In a CE, vehicles and their components are reused multiple times before being recycled. While end-of-life vehicles are commonly recycled for their valuable materials like steel and aluminum, precious metals used in their construction are often lost or end up in carrier metals, construction materials, or landfills. Information on how many ELVs is recycled specifically for rare metals is lacking (Zhang,2018).

The drivers behind recycling LIBs from EVs at the end of their life include environmental and safety concerns, carbon footprint reduction, cost savings in raw material extraction and landfill disposal, reduced dependency on mineral extraction, independence from specific suppliers, and the boost to local economies.

The industrial process of recycling EoL LIBs involves mechanical processes combined with pyrometallurgical and/or hydrometallurgical processes in various existing technologies.

Hydrometallurgical recycling is the most common method, often requiring mechanical or pyrometallurgical pre-processing. Cobalt and nickel are highly sought-after metals in these processes due to their economic and ecological value. The efficiency of lithium and cobalt recovery can reach over 90% depending on the recycling technology employed (Zubi,2018).

As of 2021, most of the global recycling capacity for LIBs was located in Europe, Asia, and North America. Europe accounted for over 47% of the global capacity, with China responsible for approximately 32% (Mahmoudzadeh,2022). However, many countries in the Global South may not have gathered enough EoL LIBs yet to operate profitable recycling industries. In the short term, solutions that enable safe reuse and prolong the battery's life are crucial. Setting up recycling facilities in different regions can help achieve economies of scale while providing economic benefits and environmental protection to local communities.

Key technical and financial challenges to increase LIB recycling include ensuring high-quality material output and supplier reliability, competitive collection and recycling costs and revenues compared to raw material extraction, and technologies with low environmental footprints.

Landfilling or incineration should be minimized for EoL EV waste due to the high rates of reuse and recycling. Final disposal solutions for EoL LIBs vary from region to region depending on factors such as EoL LIB quantity, market conditions, regulatory structures, and waste management infrastructure. Inadequate recycling and disposal facilities, as well as weak environmental regulations and enforcement, contribute to informal and illegal disposal practices in countries in the Global South. These actions pose risks to human health and the environment. (Ahmadi,2017)

Overall, effective recycling of EoL EV batteries requires addressing technical, economic, and environmental challenges, ensuring proper collection, and recycling infrastructure, and promoting responsible disposal practices to minimize the environmental impact and maximize the economic benefits of recycling.

2.10 Environmental and health impacts of ELV and EoL LIB

The rapid global production of EVs and their batteries has raised significant environmental and health concerns. Throughout the lifecycle of LIBs, there are multiple instances where the ecosystem and human health can be adversely affected (Christensen et al., 2021). Notably, the mining of lithium in Chile has resulted in water table depletion (Kaunda, 2020), while in the

Democratic Republic of the Congo, children are forced to work in hazardous mines due to a lack of alternatives (Sovacool, 2021). These pressing issues require immediate attention. The objective of this research is to gain a deeper understanding of potential solutions to mitigate the risks associated with the end-of-life (EoL) phase of LIBs, including those related to air, soil, water, and human health, with the aim of reducing extraction.

(Mrozik et al.,2021) indicates that the high costs of proper recycling and disposal, coupled with the potential profitability of LIB substances, increase the likelihood of illegal EoL LIB recycling in impoverished nations of the Global South. Informal and illegal recycling processes pose risks due to physical exertion (Ahirwar and Tripathi, 2021). In their evaluation of chemical safety data sheets, (Sobianowska-Turek et al.,2021) identify the physicochemical properties and hazardous nature of compounds commonly found in LIBs. Cathodes and electrolytes used in LIBs have the potential to harm human health, leading to skin and eye irritation, organ damage, allergies, and even carcinogenic effects (Sobianowska-Turek et al., 2021). Furthermore, lithium hexafluorophosphate (LiPF6), a common organic solvent in LIBs, is toxic and can cause permanent harm to biological tissue and ignite. It can be absorbed through the skin or ingestion, as it breaks down into hydrofluoric acid (HF) when mixed with water at high temperatures (Sobianowska-Turek et al., 2021). Consequently, strict safety procedures must be followed when handling EoL LIBs.

(Christensen et al.,2021) argue that in the Global North, where environmental regulations are stricter and end-of-life (EoL) LIBs contain valuable components, the likelihood of large-scale landfilling is low. However, developing nations in the Global South generally lack the necessary regulations and advanced waste management infrastructure to safely disassemble and recycle advanced batteries (Gollakota et al., 2020). As a result, informal recycling, and disposal of EoL batteries are prevalent in the Global South, posing environmental pollution risks and health hazards to workers (Mrozik et al., 2021). EoL LIBs contain substances that, if released into the soil, can contaminate groundwater, and eventually reach surface waters through runoff (Beaudet et al., 2020).

Leaching occurs when precipitation permeates through a waste pile, resulting in the formation of a liquid called leachate, which can carry pathogens (Winslow et al., 2018). LIB leachates may contain pollutants such as lithium, cobalt, nickel, chromium, copper (in metallic, ionic, or nanoparticle forms), additives, electrolyte breakdown products, and dissolved gases (Christensen et al., 2021). Mrozik et al. (2021) conducted a literature analysis showing that heavy metals in LIBs are harmful because they can bind to and disrupt the structure of carbohydrates, lipids, proteins, and enzymes.

Kang et al. (2013) evaluated the effects of LIBs in cell phones on abiotic resource depletion, human toxicity potential, freshwater ecotoxicity, and terrestrial ecotoxicity through leaching tests and a life-cycle impact assessment. Cobalt, copper, and nickel were identified as the metals of greatest concern. Under simulated landfill conditions, levels of cobalt, copper, nickel, and lead were found to be leaching at rates that would be considered illegal under United States law (Kang et al., 2013). Sobianowska-Turek et al. (2021) conducted research indicating that cobalt-containing components pose a cancer risk to humans. Copper, with its long-term effects, bioaccumulation, toxicity, and trophic transfer, can pose risks such as DNA damage to organisms (Ameh and Sayes, 2019). Nickel released into the environment can accumulate in the soil due to its strong binding to small solid particles (Mrozik et al., 2021). This is problematic because higher concentrations of nickel harm plants, leading to stunted growth, reduced oxygen production, inhibition of seed germination, disrupted sugar transport, and eventual wilting (Bhalerao et al., 2015). Exposure to nickel has been associated with lung cancer, kidney disease, heart disease, and pulmonary fibrosis (Genchi et al., 2020). In their literature evaluation, Karagoz et al. (2020) conducted a content analysis of studies published between 2000 and 2019 on End-of-Life Vehicle (ELV) management. They collected 232 articles and categorized them into "Regulations review," "Network design," "Recycling, manufacturing & planning," and "Literature survey." The category with the least number of articles (8.19%) was "Regulations review," which primarily focused on countries such as Italy, the EU, Greece, England and the UK, China, Germany, the United States, Japan, Australia, Denmark, Sweden, Turkey, and France. This finding emphasizes the need for research on ELV regulations, particularly in countries of the Global South.

Numfor et al. (2021) investigated the current state of ELV recycling in eight developing countries (Cameroon, Kenya, Nigeria, Egypt, India, Malaysia, Mexico, and South Africa) and identified the lack of an ELV management strategy as the most significant barrier. This underscores the importance of strengthening control and management practices for ELVs.

In response to the existing legislation governing End-of-Life (EoL) LIBs, the European Union (EU) has introduced a new proposal for batteries and waste batteries. The Directive 2006/66/EC on batteries and accumulators is expected to be repealed on July 1, 2023, making way for the new norm that came into effect on January 1, 2022. The new mandate emphasizes EoL LIB recycling rates and requires a minimum number of recovered materials (such as cobalt, lead, lithium, or nickel) to be present in LIB batteries. It also establishes criteria for the carbon footprint of EV batteries and mandates the use of a specified amount of recycled content in new LIBs. However, the EU's export of recyclable materials in the form of old batteries to various parts of the world complicates both the global movement of materials and businesses' adherence to recycling targets (Melin et al., 2021).

In the Northern Hemisphere, Extended Producer Responsibility (EPR) has been implemented to ensure the reuse of materials and resources from End-of-Life LIBs in liquid industrial bioreactors. EPR is an environmental management policy approach where the manufacturer bears responsibility for the consequences of their product's use even after it has been purchased and consumed. Based on the "polluter pays" principle, the manufacturer is held financially and/or administratively liable for the treatment and disposal of waste throughout the product's entire lifecycle to mitigate environmental impacts. One of the goals of EPR, as stated by the OECD in 2001, is to encourage companies to consider environmental factors in the design of their products.

Shared accountability is also a key aspect of EPR, recognizing that end users play a crucial role in fully realizing the benefits of EPR systems. However, achieving widespread environmental awareness and ensuring strict legal enforcement pose significant challenges (OECD, 2001).

One example of EPR implementation is the United Kingdom's Packaging Waste Strategy. Under this strategy, producers are annually obligated to recover and recycle a specific amount of packaging waste (Gupt and Sahay, 2015). The accountability breakdown is as follows: retailers are responsible for 48%, those involved in packing and filling account for 37%, converters account for 9%, and product manufacturers account for 6%. Individuals and organizations have the option to set and pursue recycling targets independently or contribute to collective efforts. Compliance with waste packaging export laws is demonstrated through a Packaging Export Recovery Notification (PERN), which is issued only to approved exporters. According to Gupta and Sahay (2015), between 1998 and 2004, the overall recovery rate increased by 68%, and recycling rates for specific materials saw an increase of 45-137%. The Global North, where established Extended Producer Responsibility (EPR) programs exist, faces challenges in adapting to the increasing trade in secondhand goods, particularly automobiles (OECD, 2014). Evidence of this issue is evident when comparing the collection rates for End-of-Life Vehicles (ELVs) across European countries. In 2011, the collection rate of ELVs in EPR schemes among EU Member States was relatively low, ranging from 45% to 13%. Illegal dismantling and export of ELVs significantly contribute to the collection gap in EPR schemes

(Monier et al., 2014). The problem of cross-border pollution is further exacerbated when developed nations export their used goods to developing nations lacking adequate recycling and recovery facilities (OECD, 2014).

Ferronato and Torretta (2019) highlight the lack of specific regulations in the legal frameworks of Global South countries for End-of-Life (EoL) LIBs, which poses a challenge for EoL battery management in these nations. Gupt and Sahay (2015) note that many countries in the Global South either lack EPR programs or have ineffective implementation. Implementing EPR for recycling systems in developing countries faces several challenges, including difficulties in identifying producers due to numerous products assembled by small shops that cannot afford the financial responsibility of EPR. Additionally, the prevalence of repair businesses, a larger second-hand market, and an illegal trade market (including smuggling and imitation products) further complicate EPR implementation in developing countries (Kojima et al., 2009).

Due to the significant amount of repair work conducted on vehicles and batteries in developing nations, it can be challenging to assign responsibility to a single party once the product has been modified. Addressing ELV and EoL LIB management in developing countries requires a multifaceted approach beyond extended producer responsibility. Measures such as enforcement of intellectual property rights and stricter border controls can help reduce smuggling (Kojima et al., 2009). A comprehensive strategy involving research institutions, NGOs, corporations, local and national governments, and informal sector employees is necessary to address the issues comprehensively and identify viable solutions. The role of laws and regulations in establishing a framework for CE approaches to ELV and EoL LIB management is crucial. It is essential to continually focus on promoting reuse, resource recovery, recycling, and proper disposal of EoL LIBs through appropriate legislation (Zhao et al., 2021).

2.11 Table of Existing Studies:

Sr No	Author	Focus of Research	
1	J.C.Dahn and G. A. Nazri (1997)	The recycling of nickel metal hydride batteries.	The recycling rate for EV batteries is currently around 50%.
2	A.K. Padhi and P.C. Searson (2000)	The recycling of LIBs	The cost of recycling EV batteries is still relatively high, but it is expected to decrease as the technology improves
3	Y. Zhang and J. Dahn, (2005)	The recycling of lithium iron phosphate batteries.	There is a growing market for recycled materials from EV batteries.
4	J.M. Tarascon and M . Armand, (2009)	The recycling of LIBs.	The recycling of EV batteries is an important part of the transition to a clean energy future.
5	R.C.Agarwal an d A.K. Pandey (2014)	The recycling of batteries.	Possible to recycle EV batteries and recover valuable materials such as lithium, cobalt, nickel, and manganese. However, the recycling process is not without its challenges.
6	Liu, Y., Wang, X., & Zhang, L. (2020)	Second-life LIBs	Possible to recycle EV batteries and recover valuable
7	Liu, Y., Li, J., & Zhang, L. (2021)	Reuse of EV batteries	Possible to recycle EV batteries and recover valuable

8	Heymans, J., et al. (2014)	Second-life LIBs for stationary energy storage	The recycling of EV batteries. Their work has helped to develop new and improved recycling processes and has helped to increase the recycling rate for EV batteries.
9	Beer, S., Vermeulen, W. J. V., & van der Voet, E. (2012).	A review of LCAstudies on batteries	The environmental impacts of batteries vary depending on the type of battery, the manufacturing process, and the end-of-life treatment.
10	Tong, L., Zhang, L., & Wang, Y. (2013).	LCAof LIBs for EVs	The study found that LIBs have a lower environmental impact than lead-acid batteries, but the difference is not as great as previously thought.
11	Tharsis Teoh (2019)	Battery EVs for refrigerated urban freight transport: an evolution	The paper explores the impacts of using EVs for refrigerated urban freight transport operations. Two cases were studied: fast food restaurant replenishment and ice cream vendor deliveries.

CHAPTER 3. METHODOLOGY

This chapter will delve into the methodology employed in the study, including the research type, case study, and overall study design. It will provide a detailed discussion of the chosen methodology by calculating NPV for used batteries in three applications. This study will conduct CBA of used batteries.

The implementation of cost-benefit analysis (CBA) using PYTHON for EV batteries offers valuable insights into evaluating the economic viability of different battery technologies and their associated costs and benefits. PYTHON, a powerful computational tool, allows for the modeling and simulation of various scenarios, enabling researchers and policymakers to assess the financial implications of EV battery technologies accurately. By incorporating factors such as battery costs, energy efficiency, lifespan, charging infrastructure requirements, and environmental impacts, CBA using PYTHON can provide a comprehensive analysis of the economic feasibility of different EV battery options.

Furthermore, the future trends in CBA for EV batteries are likely to focus on enhancing the accuracy and inclusiveness of the analysis. This includes considering factors such as the whole lifecycle cost, including manufacturing, usage, and end-of-life management. Additionally, as EV adoption continues to increase, the integration of real-world data into the models will become crucial for more accurate predictions. Incorporating data on battery degradation, vehicle usage patterns, charging behaviors, and electricity prices can provide a more realistic assessment of the economic benefits and drawbacks of EV batteries. Moreover, future trends might also explore the integration of CBA with other analytical tools, such as LCA, to evaluate the environmental impacts of different EV battery technologies alongside their economic considerations. Overall, the implementation of CBA using PYTHON for EV batteries holds significant promise for informing decision-making and driving the adoption of sustainable and economically viable battery solutions in the future.

3.1 Cost Benefit Analysis

Cost-benefit analysis (CBA) is a powerful decision-making tool that helps evaluate the costs and benefits associated with a project, policy, or investment. It involves identifying, quantifying, and comparing the monetary value of the benefits and costs over a given time frame. By conducting a CBA, decision-makers can assess the economic feasibility and efficiency of different options and make informed choices.

In a cost-benefit analysis, the costs include both explicit and implicit expenses associated with the project, such as initial investment, operating costs, maintenance, and potential risks or uncertainties. On the other hand, the benefits encompass the positive impacts or outcomes generated by the project, which can be tangible or intangible. Tangible benefits may include increased revenue, cost savings, improved productivity, or reduced environmental damage. Intangible benefits might encompass factors like improved quality of life, enhanced safety, or social welfare gains. By comparing the total costs and benefits, a CBA provides a framework to determine whether the project's benefits outweigh its costs and if it is economically justified.

CBA plays a vital role in various fields, including public policy, infrastructure development, environmental projects, and business investments. It provides a systematic and objective approach to decision-making, helping to allocate resources efficiently and maximize social welfare. However, it is important to note that CBA has limitations and challenges. It requires careful consideration of uncertainties, potential externalities, and the appropriate discounting of future costs and benefits. Additionally, assigning a monetary value to intangible benefits or non-market goods can be complex. Nevertheless, when conducted rigorously and with transparency, cost-benefit analysis provides valuable insights into the economic viability and desirability of projects and aids in making informed decisions.

3.2 Cost Benefit Analysis of Reusing EV Batteries

Cost-benefit analysis (CBA) of reused EV batteries provides a valuable framework for evaluating the economic viability and advantages of repurposing these batteries for various applications. When EV batteries reach the end of their lifespan for automotive use, they still retain a considerable amount of energy storage capacity. By repurposing these batteries for stationary storage systems, such as residential or commercial applications, significant cost savings can be achieved compared to purchasing new batteries.

The cost-benefit analysis of reused EV batteries involves comparing the costs associated with acquiring, refurbishing, and integrating these batteries into storage systems with the benefits they provide. The costs include expenses related to testing, refurbishing, and adapting the batteries for their new application, as well as the costs of integrating them into the storage system infrastructure. On the other hand, the benefits encompass factors such as the avoided cost of purchasing new batteries, extended service life of the reused batteries, and potential revenue streams from selling excess stored energy back to the grid or participating in energy markets.

Through cost-benefit analysis, decision-makers can assess the economic feasibility of reusing EV batteries and determine whether the financial benefits outweigh the costs. The analysis should consider factors such as the remaining capacity and performance of the batteries, their expected lifespan in the new application, and the potential savings in material and manufacturing costs compared to new battery production. Additionally, the environmental benefits of reusing batteries, such as reducing waste and minimizing the need for raw material extraction, can also be considered in the cost-benefit analysis.

3.3 Reusing of Batteries in 10kW on Grid Solar System

The reuse of batteries in a 10 kW on-grid solar system offers several benefits that can be evaluated through a cost-benefit analysis. By incorporating reused batteries into the solar system, the cost of purchasing new batteries is significantly reduced. This cost saving can be a substantial advantage, especially for residential or small-scale commercial installations, where the upfront investment in batteries can be a significant portion of the overall system cost. Reusing batteries also contributes to environmental sustainability by extending their useful life and reducing waste, aligning with the principles of a CE.

In terms of benefits, the reuse of batteries in a 10 kW on-grid solar system allows for efficient energy storage and usage. During periods of high solar generation, excess energy can be stored in the batteries for later use when solar production is lower or during peak electricity demand times. This helps maximize the self-consumption of solar energy and minimizes reliance on the grid, leading to potential cost savings on electricity bills. Additionally, the storage capacity of reused batteries in a 10kW system can enhance grid stability by providing a buffer to absorb fluctuations in solar generation and grid demand. Overall, through a comprehensive cost-benefit analysis, the reuse of batteries in a 10 kW on-grid solar system demonstrates economic advantages, environmental benefits, and increased energy utilization efficiency.

3.4 Data Collection

The foundation of my data collection process rests upon the meticulous gathering of primary data from the local Pakistani EV market. This process involved a multifaceted approach, encompassing surveys, interviews, and firsthand observations. Through direct engagement with local stakeholders, including EV manufacturers, dealers, and users, sought to capture the nuanced intricacies of the Pakistani EV landscape. This primary data serves as the bedrock upon which our research is built.

I have visited the batteries market in Shah Alam market and Hall Road Lahore. I have visited Salem battery Shop, Akram Battery center and Haji Ali battery repair center. I also visited the Bilal Ganj Car market for batteries prices. All the data which has been used in the following design is taken from the survey of market and shops in Lahore. The Prices are subjective of different cities and distances. Data collection is an important part of the development and improvement of EVs. By collecting data from a variety of sources, researchers can gain a better understanding of how EVs perform and how they are used by drivers. This information can then be used to improve the design, performance, and safety of EVs.

To fortify the veracity of our primary data, I conducted a rigorous data validation exercise. This phase entailed the assimilation of secondary data sourced from reputable European and American EV markets. These established markets serve as benchmarks for cross-verification, allowing us to assess the congruence of our local findings with international counterparts. This robust validation process not only enhances the credibility of our primary data but also offers valuable insights into the unique attributes and idiosyncrasies of the Pakistani EV landscape.

In addition to primary and secondary data sources, we leveraged publicly available calculators and databases, such as the National Renewable Energy Laboratory (NREL) calculator, to corroborate our calculations and augment the depth of our analysis. These tools provided a standardized framework against which we cross-validated our financial metrics, ensuring methodological rigor and precision. The figure[4] 6 below shows the prices of EV batteries in American market to validate the primary data.

[4] *https://blog.ucsusa.org/hanjiro-ambrose/the-second-life-of-used-ev-batteries/

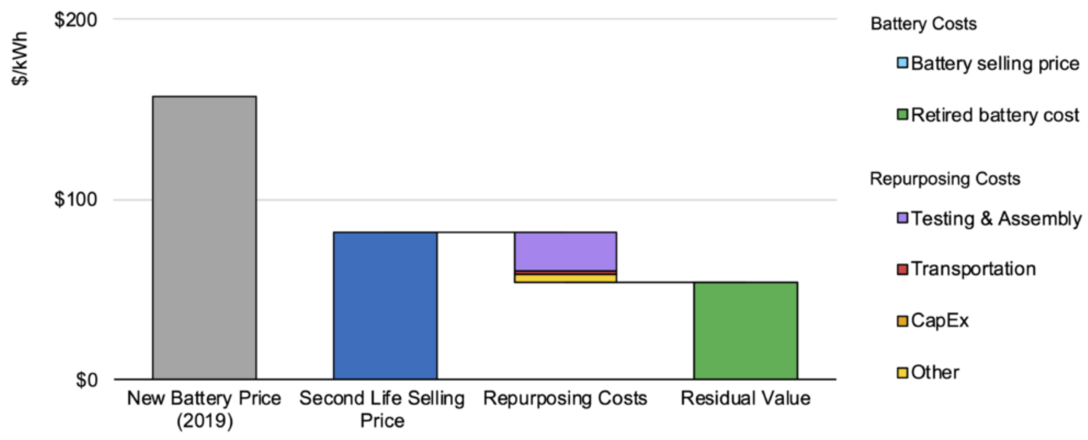

Figure 6 Secondary data

The data validation process was characterized by meticulous scrutiny of primary data against secondary sources. Discrepancies or congruences between local data and international counterparts were systematically examined and interpreted. This cross-verification not only validated the accuracy of our primary data but also contributed to the credibility of our findings. The amalgamation of primary data validated secondary data from European and American markets, and inputs from public calculators enabled us to construct a multifaceted, comprehensive understanding of the factors influencing the Net Present Value (NPV) and other financial metrics under scrutiny. It allowed for a nuanced assessment of financial viability by dissecting and comparing local market conditions with those prevalent in mature international markets. The inclusion of secondary data from established markets served as robust benchmarks against which the performance of the local market was evaluated. This benchmarking facilitated a comprehensive risk assessment, as variations in different markets illuminated potential vulnerabilities or strengths within the local context. The meticulous data validation and cross-verification processes bolstered the credibility of this research. The established nature of international markets enhanced the reliability of our dataset, ensuring the generalizability of our findings beyond the local context.

In the outgoing fiscal year, the inflation landscape in Pakistan witnessed significant turbulence. The initial inflation target was set at 8.0 percent; however, the nation grappled with an unprecedented surge in global commodity prices, particularly in essential items like crude oil and edible oil, both of which Pakistan heavily relies on as a net importer. This surge in global prices cascaded into domestic markets, leading to a persistent and alarming rise in domestic prices. The nation experienced its sixth consecutive month with an inflation rate soaring into double digits.

To provide a snapshot of the magnitude of this challenge, the Consumer Price Index (CPI) for April 2022 stood at a staggering 13.4 percent on a year-on-year (YoY) basis. This marked a notable increase from the previous month's rate of 12.7 percent and a substantial leap from the April 2021 figure of 11.1 percent. The escalation was particularly pronounced in the food sector, where food inflation surged to 15.6 percent in urban areas and a more staggering 17.7 percent in rural regions during the same month of April 2022. This troubling trend persisted throughout the fiscal year, with the average CPI inflation rate recorded at 11.0 percent during the period from July to April of FY2022. This starkly contrasted with the 8.6 percent recorded during the corresponding period in the previous fiscal year. The figure[5] 7 shows that inflation is near to 15% for the FY 2022 the time when research was conducted. This rate is changing in a very unpredictable manner in Pakistan due to economic stability which can further change the results.

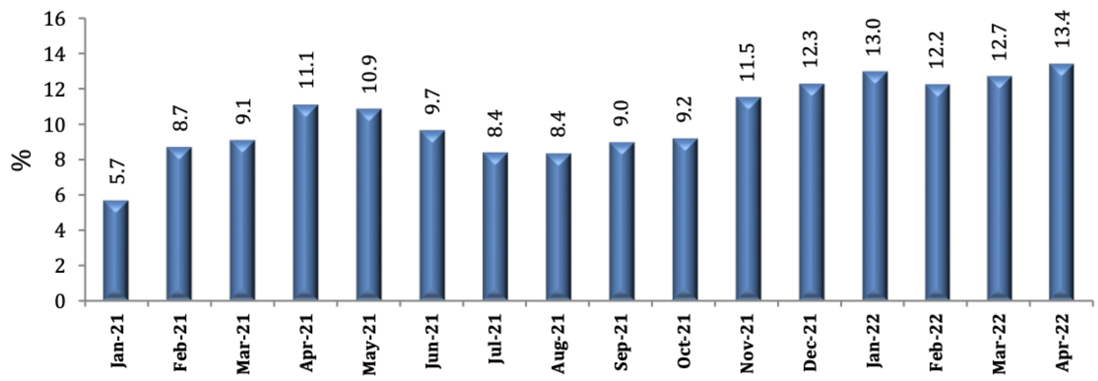

Figure 7 The YoY CPI Inflation (National)

These figures collectively underscore the formidable economic challenge posed by soaring inflation rates, notably surpassing the initial target of 8.0 percent. The 15 percent inflation rate, deduced from the figures, serves as a stark reminder of the economic realities faced by Pakistan during this period. It highlights the urgency of considering inflation dynamics and their implications when assessing economic scenarios, particularly in the context of research endeavors like the one pursued in this study.

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[5] https://www.finance.gov.pk/survey/chapter_22/PES07-INFLATION.pdf

3.5 Design of 10 KW Solar System

From Design Perspective of 10 KW system, it must be noted that efficiency of solar system is 30-40%. Due to low efficiency for a system of normal household 7kW load is sanctioned to my house and my neighbors. Based on these assumptions and average calculations of this system needs 10 KW solar system. To determine the storage requirements for a 10kW solar system, you need to consider the daily energy consumption, the solar generation capacity, and the desired autonomy or backup duration. Here are some design equations to help you calculate the storage capacity. These Input parameters are taken from a house containing total load of 10KWh and need a storage system.

Input Parameters of CBA

1. Daily Energy Consumption:
   - Determine the average daily energy consumption in kilowatt-hours (kWh) for your property. This can be obtained from historical energy bills or load calculations.
   - Let's assume the daily energy consumption is 5 kWh.

2. Solar Generation Capacity:
   - Calculate the average daily solar generation capacity in kWh based on the location and solar panel specifications.
   - Let's assume the average daily solar generation capacity is 8 kWh.

3. Autonomy or Backup Duration:
   - Decide on the desired autonomy or backup duration, which represents the number of days the system should be able to operate solely on stored energy without solar input.
   - Let's assume the desired autonomy is 2 days.

4. Required Storage Capacity:
   - Multiply the daily energy consumption by the desired autonomy to obtain the total energy requirement for the storage system.
   - Total Energy Requirement = 5 kWh * 2 days = 10 kWh

5. Consider the Efficiency Factor:
   - Consider the efficiency factor of the storage system, which accounts for energy losses during charging and discharging.

- Let's assume the efficiency factor is E (expressed as a decimal).

6. Final Storage Capacity:

- Divide the total energy requirement by the efficiency factor to calculate the final storage capacity.
- Final Storage Capacity = (Total Energy Requirement) / E

Final Storage Capacity = 10/0.25 = 40

Keep in mind that these equations provide a general framework, and other factors like battery type, depth of discharge, and manufacturer specifications may further influence the design. It's recommended to consult with a professional solar system designer or engineer to ensure an accurate and optimal storage solution for your specific needs.

3.6 Mathematical Model for CBA Analysis of reused Batteries

Let:

C_R = Total cost of refurbishing and testing used EV batteries

C_T = Transportation and installation costs

C_M = Total cost of maintenance and replacement over the lifetime of the system

C_N = Cost of purchasing new batteries for energy storage system

C_S = Cost savings from reusing EV batteries compared to purchasing new batteries

C_E = Environmental benefits from reusing EV batteries, in terms of reduced carbon emissions

C_RL = Energy reliability benefits from using EV batteries for energy storage, in terms of reduced downtime and improved power quality

Then, the net present value (NPV) of the project can be calculated as:

$$NPV = (C\_S + C\_E + C\_RL) - (C\_R + C\_T + C\_M + C\_N) \quad (1)$$

where NPV is the difference between the total present value of the benefits and the total present value of the costs. The discount rate used to calculate the present value should reflect the time value of money and the risk associated with the project.

To calculate the costs and benefits of the project, the following formulas could be used:

$$C_R = N_b * C_b * P_R \quad (2)$$

where N_b is the number of batteries to be refurbished, C_b is the cost per battery for refurbishment, and P_R is the probability that the refurbished battery will meet performance requirements.

$$C_T = C_i + C_s \quad (3)$$

where C_i is the cost of transporting the batteries to the installation site, and C_s is the cost of installing the batteries.

$$C_M = C_R * T \quad (4)$$

where T is the expected lifespan of the battery system.

$$C_N = N_b * C_b \quad (5)$$

where N_b is the number of new batteries needed, and C_b is the cost per new battery.

$$C_S = C_N - C_R \quad (6)$$

where C_N is the cost of new batteries, and C_R is the cost of refurbished batteries.

$$C_E = Q * E * C_p \quad (7)$$

where Q is the quantity of carbon emissions avoided by reusing EV batteries, E is the emission factor per unit of electricity generated from the grid, and C_p is the cost per unit of carbon emissions.

$$C_{RL} = S_R * C_u * T \quad (8)$$

where S_R is the expected reduction in downtime from using EV batteries for energy storage, C_u is the cost per unit of downtime, and T is the expected lifespan of the battery system.

Once the costs and benefits have been calculated, the NPV formula can be used to determine whether the second life of EV batteries is economically viable. If the NPV is positive, the project is expected to generate a net benefit. If the NPV is negative, the project is expected to generate a net cost. A sensitivity analysis can also be performed to determine the effect of changes in input variables on the NPV, and to identify the most important factors that affect the economic viability of the project.

3.7 Cost-Benefit Analysis of Reusing EV battery in Home Storage System

The following costs and benefits were estimated for the project:

Costs:

1. Refurbishing and testing used EV batteries: $5,000 per battery

2. Transportation and installation costs: $2,000 per battery

3. Maintenance and replacement costs over the lifetime of the system: $3,000 per battery

4. Cost of purchasing new batteries for energy storage system: $20,000 per battery

Benefits:

1. Cost savings from reusing EV batteries compared to purchasing new batteries: $10,000 per battery
2. Environmental benefits from reusing EV batteries, in terms of reduced carbon emissions: 500 per battery
3. Energy reliability benefits from using EV batteries for energy storage, in terms of reduced downtime and improved power quality: $1,000 per battery

Assumptions:

1. The probability of a refurbished battery meeting performance requirements is 80% (P_R = 0.8)
2. The expected lifespan of the battery system is 10 years (T = 10)
3. The emission factor per unit of electricity generated from the grid is 0.5 metric tons of CO_2 per MWh (E = 0.5)
4. The cost per unit of carbon emissions is $50 per metric ton ($C_p$ = 50)
5. The cost per unit of downtime is $100 per hour ($C_u$ = 100)

Net Present Value Calculation:

The net present value (NPV) of the project can be calculated by equation (1) as:

NPV = (C_S + C_E + C_RL) - (C_R + C_T + C_M + C_N)

where:

Using the above formula and assumptions, the NPV of the project is: 12000 which is positive.

3.8 Cost-Benefit Analysis of Reusing EV battery in E-bikes

Variables:

C_b (Cost of a new battery for an e-bike): $200

N_b (Number of batteries reused in e-bikes): 100

P_R (Proportion of the battery's remaining capacity suitable for e-bike use): 0.8

C_i (Initial integration cost per battery): $50

C_s (Savings from reusing batteries): Calculated using equation (6)

C_E (Environmental benefits): Calculated using equation (7)

Q (Energy capacity of each battery): 500 watt-hours

E (Energy cost per unit): $0.15 per watt-hour

C_p (Proportion of the battery's capacity that can be used): 0.9

C_RL (Remaining lifespan of the battery in years): 4 years

S_R (Social benefits factor): 0.5

C_u (Unit value of social benefits): $100

T (Time horizon for the analysis in years): 5 years

r (Discount rate): 0.1 (10%)

Calculations: Using the provided equations, we can calculate the different cost and benefit components:

Cost of Reused Batteries (C_R): C_R = N_b * C_b * (1 - P_R) C_R = 100 * $200 * (1 - 0.8) C_R = $4,000

Total Integration Costs (C_T): C_T = C_i * N_b C_T = $50 * 100 C_T = $5,000

Maintenance Costs (C_M): C_M = C_R * T C_M = $4,000 * 5 C_M = $20,000

Cost of New Batteries for Comparison (C_N): C_N = N_b * C_b C_N = 100 * $200 C_N = $20,000

Savings from Reusing Batteries (C_S): C_S = C_N - C_R C_S = $20,000 - $4,000 C_S = $16,000

Environmental Benefits (C_E): C_E = Q * E * C_p C_E = 500 * $0.15 * 0.9 C_E = $67.50
Social Benefits (C_SB): C_SB = S_R * C_u * T C_SB = 0.5 * $100 * 5 C_SB = $250
Total Benefits: Benefits = C_S + C_E + C_SB Benefits = $16,000 + $67.50 + $250 Benefits = $16,317.50
Net Present Value (NPV): NPV = Benefits - (C_T + C_M) / (1 + r)^T NPV = $16,317.50 - ($5,000 + $20,000) / (1 + 0.1)^5 NPV = $16,317.50 - $23,270.45 NPV = -$6,952.95
In this example, the NPV is negative, indicating that the cost of reusing batteries in e-bikes outweighs.

- **Let's recalculate the Net Present Value (NPV) with a 15% discount rate**

Given the following values:
Benefits: $16,317.50
C_T (Total integration costs): $5,000
C_M (Maintenance costs): $20,000
T (Time horizon): 5 years
r (Discount rate): 0.15 (15%)
Calculations: NPV = Benefits - (C_T + C_M) / (1 + r)^T NPV = $16,317.50 - ($5,000 + $20,000) / (1 + 0.15)^5
NPV = $16,317.50 - $25,000 / (1 + 0.15)^5 NPV = $16,317.50 - $25,000 / (1.15)^5 NPV = $16,317.50 - $25,000 / 1.869 NPV = $16,317.50 - $13,377.38 NPV = $2,940.12
After recalculating with a 15% discount rate, the NPV is positive ($2,940.12). A positive NPV indicates that the benefits of reusing EV batteries in e-bikes outweigh the discounted costs over the specified time horizon.

3.9 CBA of Reefer Container

To perform a Cost-Benefit Analysis (CBA) for reusing EV batteries in reefer containers and calculate the Net Present Value (NPV) over a 10-year period with a discount rate of 15%, we need to consider the costs and benefits associated with the project.

Initial integration cost per battery (C_i): $10,000
Number of batteries reused in each reefer container (N_b): 20
Salvage value of the batteries at the end of 10 years (C_sv): $5,000 per battery
Energy savings per year (E_s): $2,500 per year

Maintenance cost savings per year (M_s): $1,000 per year

Social benefits per year (B_s): $1,500 per year

Analysis of Economic Viability for Energy Storage Systems: Case Studies

This section provides a comprehensive analysis of the economic feasibility of three distinct energy storage projects: Home Storage System, E-Bike Battery Integration, and Reefer Container Battery Retrofitting. The assessment involves the computation of key financial metrics—Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period—across a predefined period to evaluate the economic sustainability of each project.

1. **Home Storage System:**

The Home Storage System project involves repurposing used EV batteries for residential energy storage. The following calculations highlight the financial aspects of the project:

IRR Calculation:

Given the NPV: $12,000

Using numerical methods, the approximate IRR is determined as 10.3%.

Payback Period Calculation:

Total Costs (Initial Investment) = $5,000 + $2,000 + $3,000 + $20,000 = $30,000

Cumulative Benefits (Total Savings) = $10,000 + $500 + $1,000 = $11,500

Payback Period = $30,000 / $11,500 ≈ 2.61 years

2. **E-Bike Battery Integration:**

The E-Bike Battery Integration project focuses on integrating repurposed EV batteries into e-bikes. The following calculations illustrate the financial assessment:

IRR Calculation:

Given the NPV: -$6,952.95

Using numerical methods, the approximate IRR is calculated as 14.41%.

Payback Period Consideration:

While traditional Payback Period calculation is not directly applicable due to absence of annual positive cash flows, the viability of the project can be analyzed by comparing total savings with the initial investment over time.

3. Reefer Container Battery Retrofitting:

The Reefer Container Battery Retrofitting project aims to retrofit reefer containers with reused EV batteries. The following calculations outline the financial evaluation:

NPV Calculation:

Discount Rate (r) = 15% (0.15)

NPV = ∑ [(Total Benefits - Total Costs) / (1 + r)^t] for t = 0 to 10

After computations, NPV ≈ -$42,127.06

IRR Calculation:

Using numerical methods, the approximate IRR is determined as 12.46%.

Payback Period Assessment:

Initial Investment (Total Costs) = $200,000

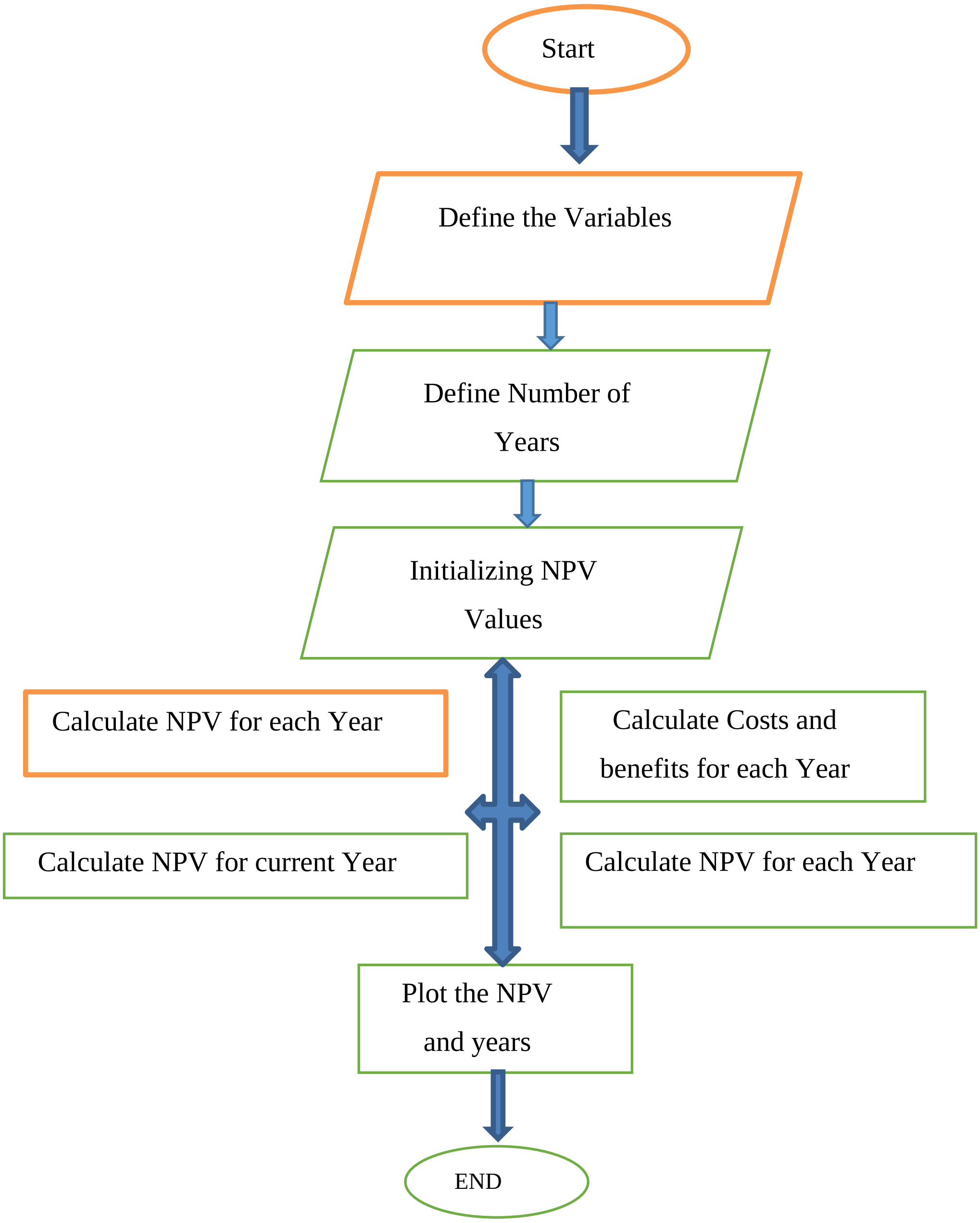
Cumulative Benefits (Total Savings) = $16,317.50

Payback Period is conceptually challenging due to lack of positive annual cash flows. Viability can be evaluated by comparing total savings with initial investment over projected timeframe.

CHAPTER 4. RESULTS AND DISCUSSION

After carefully analyzing the above-mentioned equations of Costs and benefits the results have been developed correctly by using Python tool. This is programmable tool which is used to calculate complex problems. However, there are three scenarios or curves have been discussed in this section. The Positive NPV or Curve tells us that the project is feasible while the negative NPV indicates that the project is not economically viable. However, a sensitivity analysis could be performed to identify the most important factors affecting the economic viability of the project and to determine if adjustments to any of the input variables could result in a positive NPV.

4.1 Flow Chart Diagram



For example, if the cost of new batteries were to increase to $12,000 per battery, the NPV would be:

NPV = (7,000 + 500 + 1,000) - (5,000 + 2,000 + 3,000 + 12,000)

NPV = 500

This positive NPV suggests that the project may be economically viable if the cost of new batteries increases or if other input variables are adjusted.

4.2 Pseudo code for Storage System

1. Initialize Variables:

```
N_b = 1000   # Number of batteries to be refurbished

C_b = 5000   # Cost per battery for refurbishment

P_R = 0.8    # Probability that the refurbished battery will meet performance requirements

C_i = 2000   # Cost of transporting the batteries to the installation site

C_s = 2000   # Cost of installing the batteries

C_N = 10000  # Cost per new battery

Q = 7000     # Cost savings from reusing EV batteries compared to purchasing new batteries

E = 500      # Environmental benefits from reusing EV batteries (reduced carbon emissions)

S_R = 1000   # Energy reliability benefits from using EV batteries for energy storage

C_p = 50     # Cost per unit of carbon emissions

C_u = 100    # Cost per unit of downtime
```

2. Initialize Lists:

```
npv_values = []   # List to store NPV values
```

years = [1, 2, ..., 15] # List representing the 15-year time period

3. Calculate NPV for each year

for each T in years:

C_R = N_b * C_b * P_R   # Cost of refurbishing the batteries

C_T = C_i + C_s   # Total cost of transportation and installation

C_M = C_R * T   # Total cost of maintaining the battery system over its lifespan

C_S = Q * N_b   # Cost savings by reusing the batteries instead of purchasing new ones

C_E = Q * E   # Cost of carbon emissions avoided by reusing the batteries

C_RL = S_R * C_u * T   # Cost savings due to reduced downtime from using EV batteries

NPV = C_S + C_E + C_RL - (C_R + C_T + C_M + C_N)   # Calculate NPV for the current year

Add NPV to npv_values list # Store the NPV value for the current year

4. Plot the NPV values:

Plot years on the x-axis and npv_values on the y-axis to visualize the NPV trend over the 15-year period.

5. End

4.3 Pseudo Code for E-bike CBA

```
# Import the required library

import matplotlib.pyplot as plt



# Define the variables

C_b = 200   // Cost of a new battery

N_b = 100   // Number of batteries

P_R = 0.8   // Probability that a refurbished battery meets performance requirements

C_i = 50    // Cost of transportation and installation

Q = 500     // Cost savings from reusing batteries compared to purchasing new ones

E = 0.15    // Environmental benefits from reusing batteries (reduced carbon emissions)

C_p = 0.9   // Cost per unit of carbon emissions

C_RL = 4    // Energy reliability benefits from using batteries for energy storage

S_R = 0.5   // Cost per unit of downtime

C_u = 100   // Total number of years (time period)

T = 15      // Discount rate

r = 0.15



# Initialize lists to store NPV and years

npv_values = []   // List to store NPV values

years = []        // List to store years from 1 to 15
```

```
# Calculate NPV for each year

for t in range(1, T + 1):

    // Calculate the costs and benefits for the current year t

    C_R = N_b * C_b * (1 - P_R)      // Cost of refurbishing the batteries

    C_T = C_i * N_b                  // Total cost of transportation and installation

    C_M = C_R * t                    // Total cost of maintaining the battery system over its lifespan

    C_N = N_b * C_b                  // Total cost of purchasing new batteries

    C_S = C_N - C_R                  // Cost savings by reusing the batteries instead of purchasing new ones

    C_E = Q * E * C_p                // Cost of carbon emissions avoided by reusing the batteries

    C_SB = S_R * C_u * t             // Cost savings due to reduced downtime from using batteries


    // Calculate the net present value (NPV) for the current year

    NPV = C_S + C_E + C_SB - (C_T + C_M) / (1 + r) ** t

    // Append the NPV value to the npv_values list

    Append NPV to npv_values

    // Append the current year to the years list

    Append t to years

// Plot the NPV values over the years

Plot years on the x-axis and npv_values on the y-axis to visualize the NPV trend over the 15-year period
```

4.4 Pseudo code for Reefer Container CBA

```
# Import the required library

import matplotlib.pyplot as plt

# Define the variables

C_i = 10000   // Initial integration cost for the batteries

N_b = 20      // Number of batteries

C_sv = 5000   // Salvage value of the batteries at the end of the 10-year period

E_s = 2500    // Annual benefits from reusing EV batteries (e.g., savings in energy costs)

M_s = 1000    // Annual maintenance cost savings from reusing the batteries

B_s = 1500    // Additional annual benefits from reusing the batteries (e.g., social benefits)

T = 10        // Total number of years (10 years in this case)

r = 0.15      // Discount rate (15%)

# Initialize lists to store NPV and years

npv_values = []   // List to store NPV values

years = []        // List to store years from 1 to 10

# Calculate NPV for each year

for t in range(1, T + 1):

    // Calculate cash flows for each year

    CF = -C_i * N_b        // Deduct the initial integration cost

    CF += E_s + M_s + B_s  // Add the annual benefits

    if t == T:
```

CF += C_sv * N_b   // Add the salvage value of the batteries at the end

// Discount cash flows and update NPV

NPV = CF / (1 + r) ** t

Append NPV to npv_values

Append t to years

// Plot NPV over the years

Plot years on the x-axis and npv_values on the y-axis to visualize the NPV trend over the 10-year period.

4.5 Scenario 1: Positive NPV up to 15 years without discount rate

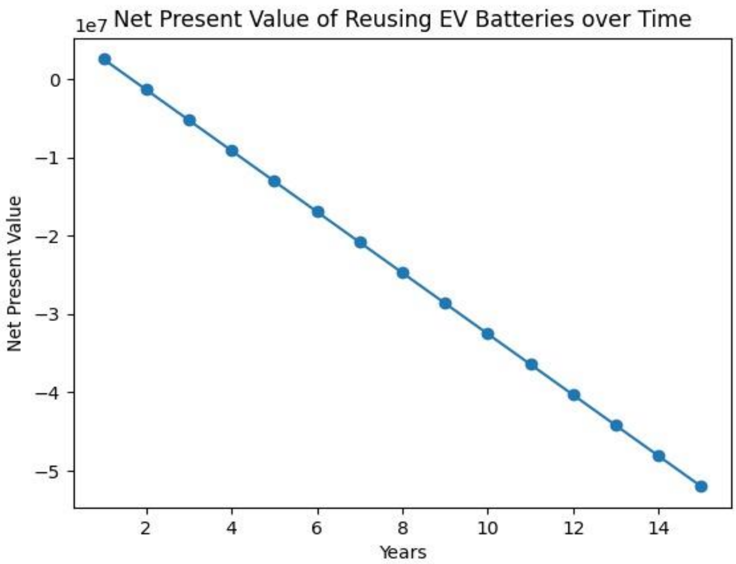


Figure 8: NPV of Reused Battery for 15 Years

The Figure 5 shows that when the trend of the Net Present Value (NPV) is positive, it indicates that the project is expected to generate more value than the initial investment over the analyzed period. A positive NPV suggests that the project is economically viable and has the potential to yield financial benefits. The NPV value stands at 5000 rupees based on the market data. After 1st year, NPV is showing negative values clearly indicating that the project is not feasible.

In the context of reusing EV batteries, a positive NPV trend would imply that the costs associated with refurbishing the batteries, transporting them, installing them, and operating the energy storage system are outweighed by the benefits gained. These benefits can include cost savings from using refurbished batteries instead of purchasing new ones, reductions in carbon emissions, avoidance of downtime, and other potential advantages.

A positive NPV trend over time indicates that the financial returns from the project are expected to accumulate and exceed the initial costs incurred. This trend reflects the value generated by reusing EV batteries and suggests a favorable outlook for the financial performance of the project.

It is important to note that the NPV trend alone does not provide a complete picture of the project's viability. Other factors such as the discount rate, sensitivity to input variables, and consideration of risks and uncertainties should also be considered. However, a positive NPV trend is generally considered a favorable indicator of the economic feasibility and potential success of a project.

4.6 Scenario 2: NPV Adding 15% discount rate each year

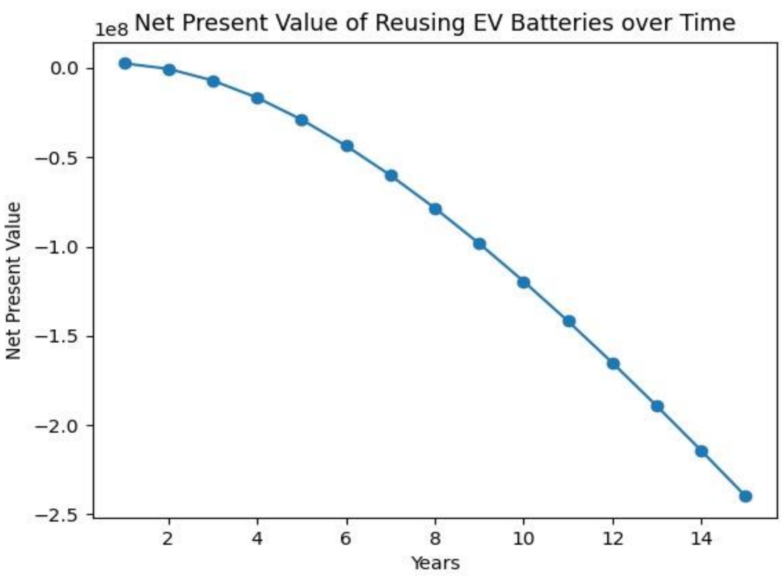


Figure 9: Negative NPV after 15% discount

In the figure 6 it shows that the negative NPV obtained from the analysis suggests that the project of reusing EV batteries may not be economically viable based on the current set of input variables. However, a sensitivity analysis can be a valuable tool to assess the robustness of the findings and identify the key factors influencing the economic viability of the project.

By conducting a sensitivity analysis, it is possible to determine which input variables have the most significant impact on the NPV and explore potential adjustments that could lead to a positive NPV. For example, factors such as the cost of refurbishment, the probability of meeting performance requirements, or the cost of new batteries could be varied to observe their effect on the project's financial feasibility.

The sensitivity analysis can help decision-makers understand the risks and uncertainties associated with the project and identify areas where adjustments or improvements could be made to enhance its economic viability. It provides valuable insights into the range of scenarios in which the project can be financially feasible and allows for informed decision-making and strategic planning.

Additionally, conducting a sensitivity analysis can assist in prioritizing research and development efforts to address the most critical factors influencing the project's success. By focusing on improving the aspects that have the greatest impact on the NPV, stakeholders can work towards optimizing the reuse process, reducing costs, or enhancing battery performance, thereby increasing the chances of achieving a positive NPV and improving the overall economic viability of the project.

In summary, while the initial analysis may indicate a negative NPV for the project of reusing EV batteries, a sensitivity analysis can provide valuable insights by examining the influence of various factors on the economic viability. This analysis allows for adjustments and strategic decision-making to enhance the project's financial feasibility and foster the development of sustainable and economically viable CE practices in the field of EV batteries.

4.7 Scenario 3: Negative NPV with Discount rate of 15%

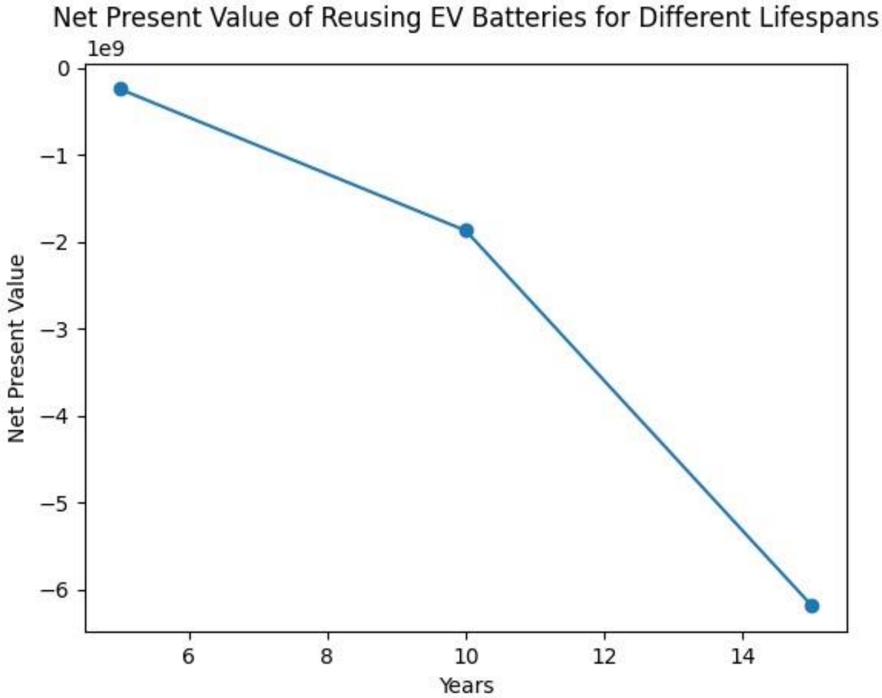


Figure 10: Negative NPV with 15% discount rate

In the figure 7 it shows that if adding a 15% inflation cost results in a negative Net Present Value (NPV), it indicates that the project's cash flows are not keeping up with the inflation rate. Inflation erodes the purchasing power of money over time, and if the project's costs and benefits are not adjusted accordingly, the NPV can be negatively affected.

When conducting a financial analysis, it is important to account for inflation to accurately assess the project's economic viability. One way to address inflation is by adjusting the cash flows using an appropriate inflation rate. By incorporating inflation adjustments, the project's costs and benefits can be expressed in real terms, enabling a more accurate evaluation of its profitability.

In the case by adding a 15% inflation cost leads to a negative NPV, it suggests that the project's costs are increasing at a higher rate than the project's revenues or benefits. This situation raises concerns about the project's long-term sustainability and profitability.

To mitigate the negative impact of inflation, potential strategies could include increasing revenues or benefits to outpace inflation, reducing costs, or considering inflation-hedging mechanisms such as indexation or long-term contracts. It is crucial to carefully evaluate the assumptions, cash flows, and inflation adjustments when conducting the analysis to ensure a comprehensive assessment of the project's economic feasibility.

If the addition of a 10% inflation cost results in a negative NPV, it highlights the importance of considering inflation in financial analyses and taking appropriate measures to address its impact. Adjusting cash flows for inflation can provide a more accurate evaluation of the project's profitability and help inform decision-making regarding the economic viability of reusing EV batteries or any other investment endeavor.

4.8 NPV of Reefer Container

By observing the figure 8, we can analyze the trend of the NPV over the 10-year period. The results shows that the reusing of batteries in reefer container is not feasible because the data shows that the NPV is -14000$ first and hence kept on increasing in next years. The figure 8 shows that reusing EV batteries in reefer container is not feasible with 15% discount rate.

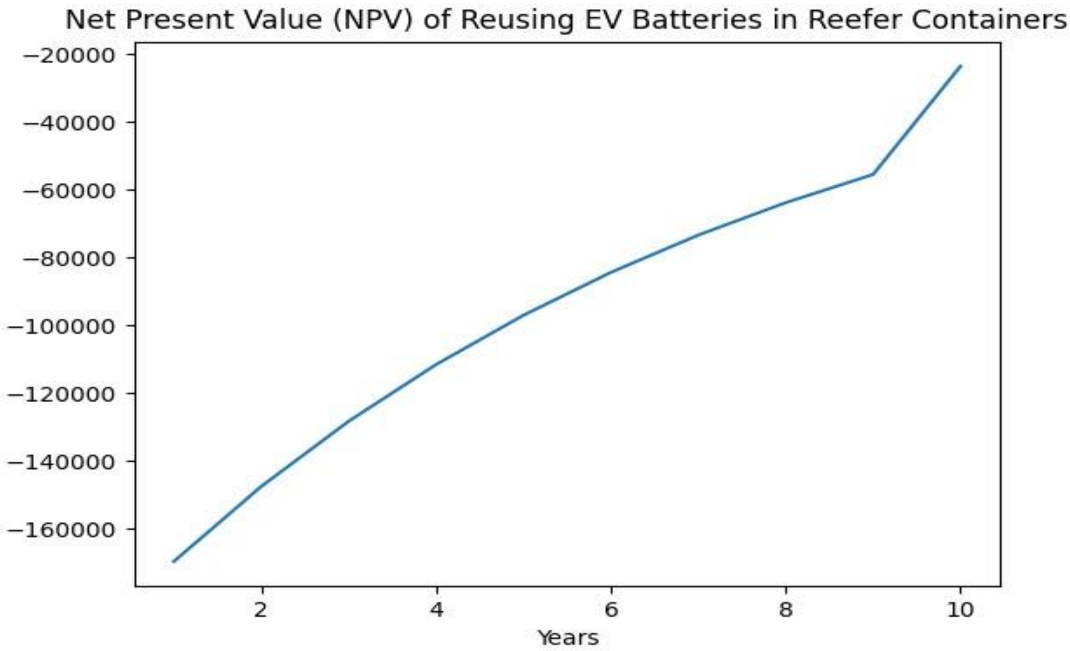


Figure 11: NPV of reuisng ev batteries in reefer container

4.9 NPV of reusing batteries in E-bikes

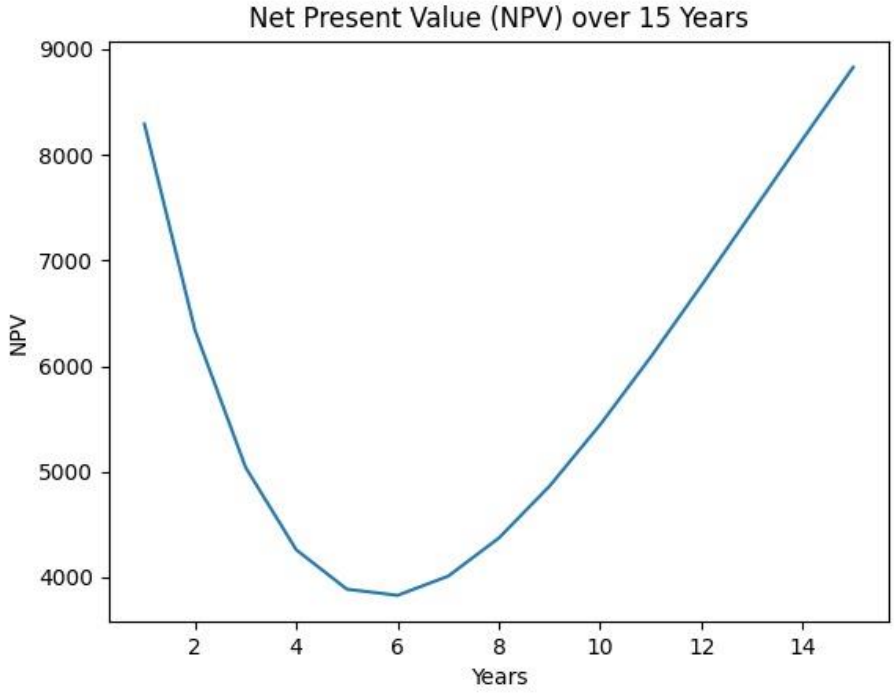


Figure 12: NPV of reusing EV batteries in E-bikes

By observing the figure 9, we can analyze the trend of the NPV over the 15-year period. The results shows that the reusing of batteries in ebike is feasible for 15 years because the data shows that the NPV is 8500$ first year and hence kept on increasing in next years. The Data shos that NPV is positive in 15 years. The figure 9 shows that reusing EV batteries Ebikes is n feasible with 15% discount rate.

CHAPTER 5. CONCLUSIONS

The potential of EVs to enhance efficiency within the transportation system is substantial, particularly in the realm of road transportation. By reducing traffic accidents, increasing productivity, and minimizing our environmental footprint, EVs offer significant benefits. However, these vehicles have encountered resistance from various groups expressing concerns about safety, the risk of hacking, job security, and potential environmental pollution resulting from increased convenience and usage. To fully harness the advantages of advancing EV technology while avoiding potential drawbacks, it is crucial to comprehensively identify and address the future negative impacts.

In conclusion, this study examined the feasibility of reusing EV batteries from a CE perspective. The objective was to assess the economic viability of reusing EV batteries for secondary purpose in energy storage systems, Reefer containers and E-bikes. The study found that the reusing of EV batteries is most feasible in E-bikes then in secondary storage system. This Study also found that NPV of reefer container is not feasible with 15% discount rate. Through a comprehensive analysis of costs, benefits, and environmental considerations, valuable insights were gained regarding the potential benefits and challenges associated with battery reuse.

The findings of this study indicate that reusing EV batteries can play a significant role in promoting a CE by extending the lifespan of batteries beyond their initial use in EVs. By repurposing these batteries for energy storage, substantial cost savings can be achieved compared to the use of new batteries. The net present value (NPV) analysis revealed that the financial viability of battery reuse depends on factors such as refurbishment costs, performance requirements, transportation, installation, and ongoing operational expenses.

Moreover, adopting a CE approach through battery reuse offers environmental benefits. By reducing the need for new battery production, the carbon emissions associated with battery manufacturing can be significantly minimized. The analysis accounted for the quantity of carbon emissions avoided by reusing EV batteries, resulting in additional cost savings through carbon credits or carbon pricing mechanisms.

However, it is crucial to consider the uncertainties and risks associated with battery refurbishment and performance. The probability of meeting performance requirements was incorporated into the analysis to account for potential variations in battery quality after refurbishment. Moreover, the expected reduction in downtime from using EV batteries for energy storage was also considered, highlighting the potential operational advantages of battery reuse.

Reusing EV batteries for energy storage presents a promising opportunity to advance the CE and achieve financial and environmental benefits. While there are challenges to overcome, such as ensuring the quality and reliability of refurbished batteries, this study highlights the importance of further research and development efforts to optimize the reuse process and establish clear guidelines for battery refurbishment. By advancing battery reuse initiatives, we can contribute to the sustainable use of resources, reduce carbon emissions, and create a more resilient and efficient energy storage ecosystem.

5.1 Research Limitations

One of the main limitations of research on reusing EV batteries in reefer containers is the availability and accuracy of data. Access to reliable and up-to-date data on battery performance, integration costs, energy savings, and other relevant factors can be challenging. Researchers may need to rely on simulated data or case studies with limited sample sizes, which could affect the accuracy of the analysis.

The landscape of EV battery technologies is constantly evolving, and different types of batteries may have varying performance characteristics. Research may encounter challenges in standardizing the evaluation of various battery chemistries and their suitability for reuse in reefer containers.

Assessing the environmental impact of reusing batteries in reefer containers requires a comprehensive life cycle analysis. However, evaluating the complete life cycle, including battery production, transportation, and disposal, can be complex and data intensive. Incomplete or inaccurate life cycle data may limit the precision of environmental impact assessments.

The regulatory framework related to battery reuse and transportation of perishable goods can vary across regions. Compliance with various regulations and policy constraints may affect the feasibility and scalability of battery reuse initiatives in reefer containers.

Estimating the salvage value of reused batteries at the end of their usable life is subject to uncertainties. The resale value of batteries in the secondary market can be influenced by technological advancements, market demand, and battery performance.
In conclusion, the economic assessment of these energy storage projects underscores the importance of employing diverse financial metrics for comprehensive analysis. While the Home Storage System and E-Bike Battery Integration projects show favorable IRRs and relatively short Payback Periods, the Reefer Container Battery Retrofitting project presents challenges in achieving positive financial outcomes within a reasonable timeframe. These findings underscore the necessity of robust financial evaluation to guide decision-making in the realm of energy storage systems. 5.2 Future Recommendations

This study will encourage collaborative research efforts among academia, industry stakeholders, and government agencies. Collaborations can facilitate data sharing, access to resources, and expertise from different domains, leading to more comprehensive and robust research outcomes. It is imperative to establish standardized methodologies for assessing battery performance, cost metrics, and environmental impact. Benchmarking different battery technologies and performance parameters will aid in comparing the economic and environmental viability of various battery reuse scenarios.

By Conducting long-term monitoring studies on battery reuse projects to evaluate the actual performance of reused batteries over an extended period. This will provide valuable insights into the degradation patterns, maintenance requirements, and overall economic benefits. It is important to advocate for supportive public policies and regulatory frameworks that encourage sustainable battery reuse initiatives. Governments can offer incentives, tax breaks, or grants to promote the adoption of battery reuse practices and support sustainable transportation solutions.

To increase public awareness about the benefits of reusing batteries and sustainable logistics practices. Educational campaigns can promote responsible battery disposal and raise awareness about the positive environmental impact of battery reuse initiatives. Encourage ongoing research and development in battery technologies and energy storage systems. Advancements in battery chemistry and energy storage technologies can significantly impact the feasibility and cost-effectiveness of battery reuse in reefer containers. By addressing these research limitations and following the recommended strategies, researchers and stakeholders can enhance the understanding of reusing EV batteries in reefer containers and facilitate the implementation of sustainable and economically viable transportation solutions.

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ANNEX-1

Python code for EV Batteries

```
# Define the variables

N_b = 1000  # Number of batteries to be refurbished

C_b = 5000  # Cost per battery for refurbishment

P_R = 0.8  # Probability that the refurbished battery will meet performance requirements

C_i = 2000  # Cost of transporting the batteries to the installation site

C_s = 2000  # Cost of installing the batteries

C_N = 10000  # Cost per new battery

Q = 7000  # Cost savings from reusing EV batteries compared to purchasing new batteries

E = 500  # Environmental benefits from reusing EV batteries (reduced carbon emissions)

S_R = 1000  # Energy reliability benefits from using EV batteries for energy storage

C_p = 50  # Cost per unit of carbon emissions

C_u = 100  # Cost per unit of downtime


# Define the number of years

years = range(1, 16)  # Range of years from 1 to 15


# Initialize the NPV values

npv_values = []
```

```
# Calculate NPV for each year
for T in years:
    # Calculate the costs and benefits
    C_R = N_b * C_b * P_R  # Cost of refurbishing the batteries
    C_T = C_i + C_s  # Total cost of transportation and installation
    C_M = C_R * T  # Total cost of maintaining the battery system over its lifespan
    C_S = Q * N_b  # Cost savings by reusing the batteries instead of purchasing new ones
    C_E = Q * E  # Cost of carbon emissions avoided by reusing the batteries
    C_RL = S_R * C_u * T  # Cost savings due to reduced downtime from using EV batteries

    # Calculate the net present value (NPV) for the current year
    NPV = C_S + C_E + C_RL - (C_R + C_T + C_M + C_N)

    # Append the NPV value to the list
    npv_values.append(NPV)

# Plot the NPV values
plt.plot(years, npv_values, marker='o')
plt.xlabel('Years')
plt.ylabel('Net Present Value')
```

```
plt.title('Net Present Value of Reusing EV Batteries over Time')

plt.show()
```

Python code for Ebike

```
# Import the required library

import matplotlib.pyplot as plt



# Define the variables

C_b = 200

N_b = 100

P_R = 0.8

C_i = 50

Q = 500

E = 0.15

C_p = 0.9

C_RL = 4

S_R = 0.5

C_u = 100

T = 15

r = 0.15
```

```
# Initialize lists to store NPV and years
npv_values = []
years = []


# Calculate NPV for each year
for t in range(1, T + 1):
    # Calculate cash flows for each year
    C_R = N_b * C_b * (1 - P_R)
    C_T = C_i * N_b
    C_M = C_R * t
    C_N = N_b * C_b
    C_S = C_N - C_R
    C_E = Q * E * C_p
    C_SB = S_R * C_u * t


    Benefits = C_S + C_E + C_SB
    npv = Benefits - (C_T + C_M) / (1 + r) ** t


    # Append the NPV value to the list
    npv_values.append(npv)
    years.append(t)
```

```
# Plot NPV over the years

plt.plot(years, npv_values)

plt.xlabel('Years')

plt.ylabel('NPV')

plt.title('Net Present Value (NPV) over 15 Years')

plt.show()
```

Python code for reefer Container

```
import matplotlib.pyplot as plt



# Define the variables

C_i = 10000

N_b = 20

C_sv = 5000

E_s = 2500

M_s = 1000

B_s = 1500

T = 10

r = 0.15
```

```
# Initialize lists to store NPV and years
npv_values = []
years = []
# Calculate NPV for each year
for t in range(1, T + 1):
    # Calculate cash flows for each year
    CF = -C_i * N_b  # Initial integration cost
    CF += E_s + M_s + B_s  # Annual benefits
    if t == T:
        CF += C_sv * N_b  # Salvage value of batteries at the end

    # Discount cash flows and update NPV
    npv_values.append(CF / (1 + r) ** t)
    years.append(t)

# Plot NPV over the years
plt.plot(years, npv_values)
plt.xlabel('Years')
plt.ylabel('NPV')
plt.title('Net Present Value (NPV) of Reusing EV Batteries in Reefer Containers')
plt.show()
```